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DIGITAL SHAFT ENCODER

GENERAL ELECTRIC COMPANY
1 JIMSON ROAD
CINCINNATI, OHIO 45215

DECEMBER 1976

TECHNICAL REPORT AFAPL-TR-76-106
FINAL REPORT FOR PERIOD FEBRUARY 1974 - OCTOBER 1976

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AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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This report documents the design, test, and development of a high temperature digital rotary position transducer. Use of magnetic sensors in this shaft encoder eliminates the need for brushes or light sources to create the eight-bit digital output signal. Included in the project was environmental testing and on-engine operation. A digital electronic readout instrument was built to aid circuit development and testing. The simple construction of the encoder makes this device well suited for aircraft engine applications.

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PREFACE

The development of a high temperature digital shaft encoder was aimed at providing a digital position transducer that is compatible with digital electronic controls. Analog devices require analog-to-digital converters in order to interface with digital electronics. Achnowledgment is made to Singer-Librascope for their major technical contribution to this project. Appreciation is expressed to Dan Frey of GE Evendale for his contribution to the development of the encoder (the design and development of the electrical unit for excitation and readout).

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1.0 SUMMARY

A prototype digital shaft encoder for use as a digital position transducer for jet engine controls was designed, built, and tested. The importance of a digital output signal is that interfacing with a digital computer is simplified. The primary effort was aimed at developing an encoder capable of good performance while withstanding a jet engine environment.

The eight-bit, magnetic, Gray code encoder met all functional requirements except at 400° F. At 400° F, the performance was limited by the magnetic properties of the ferrite transformer cores available at that time.

Testing included thermal cycling, temperature to 400° F, vibration, life test, and on-engine operation. Some problems were encountered. It was found that a thermal barrier had to be added to reduce the thermal stresses in the ferrite transformers during temperature cycling. During the first vibration test, a ferrite core was broken by the wedging of an aluminum chip between the core and disk. During the second vibration test, unsupported loops of the primary windings abraded the inside diameter of the cores. The configuration that successfully passed the vibration test included reduced wire size, reverse coil winding, and improved potting of the wires. A bearing failure, attributed to running three vibration tests with the same bearings, occurred during the first life test. A new set of bearings was substituted and the encoder subsequently passed the life test successfully. Two ferrite cores were broken during the on-engine test. The on-engine failure was probably initiated by an aluminum chip wedging between the core and the disk. More care must be taken in cleaning the parts and during assembly to avoid generating chips.

The experience gained from this program and the development of a new core material, which occurred since the fabrication of these encoders, provides an excellent background for a future effort.

2.0 INTRODUCTION

Advanced turbine engines are becoming increasingly more complex. As a result, more stringent demands are being placed on engine control systems for faster response and accuracy.

In order to take full advantage of digital techniques, digital sensors are needed. This program encompassed the design, development, and testing of an absolute magnetic shaft encoder that is compatible with digital control techniques. Present transducers such as the linear variable differential transformer (LVDT) and the potentiometer are analog devices whose output signal requires additional processing to be compatible with a digital control. Commercial use of digital shaft encoders is increasing but there was nothing available suitable for the jet engine environment. Under the sponsorship and direction of Aero Propulsion Laboratory, Wright-Patterson Air Force Base (Contract F33615-74-C-2007), a magnetic absolute digital shaft encoder has been under development. The Air Force project engineer was Charles A. Skira, AFAPL/TBC.

The broad objective of this program has been to design and develop a prototype shaft encoder compatible with digital controls and capable of withstanding a jet engine environment. Specifically, the program was to complete the following:

1. Issue a specification and an envelope drawing for the digital shaft encoder. The specification was to be similar to those in current use for position transducers, the maximum temperature being 400° F. A servo-type mounting was specified by the envelope drawing.

2. The operational requirements of the encoder were to be established for a fully realistic engine-type application.

3. The encoder would be designed as an eight-bit, magnetic Gray code encoder.

3.0 BACKGROUND

Based on previous General Electric experience with linear variable differential transformers and vendor information, a specification was issued (see Appendix A). A market survey of listed encoder vendors revealed only one vendor producing magnetic encoders. Because of the high temperature requirements (400° F), a magnetic encoder was desired. The only vendor responding to the Request for Quote was:

Singer-Librascope
833 Sonora Avenue
Glendale, California 91201

This program consisted of two parts: (1) build and test a 250° F eight-bit, Gray code encoder, (2) based on the learning in the first part, build and test a 400° F eight-bit, Gray code encoder. The second part was to include on-engine and some Design Assurance testing.

The two 250° F encoders designed and built by Singer-Librascope were designated Model Number 878-23-000 (see Figure 1). Some high temperature features were incorporated as a head-start effort. Three 400° F encoders were designed and built, two for General Electric Engineering and one for Design Assurance Testing. All units conformed with design, manufacturing, and material requirements of General Electric Specification M50TF2.

Achnowledgment is made of information and data provided by Singer-Librascope, who designed and manufactured the shaft encoders under subcontract in accordance with General Electric specifications.

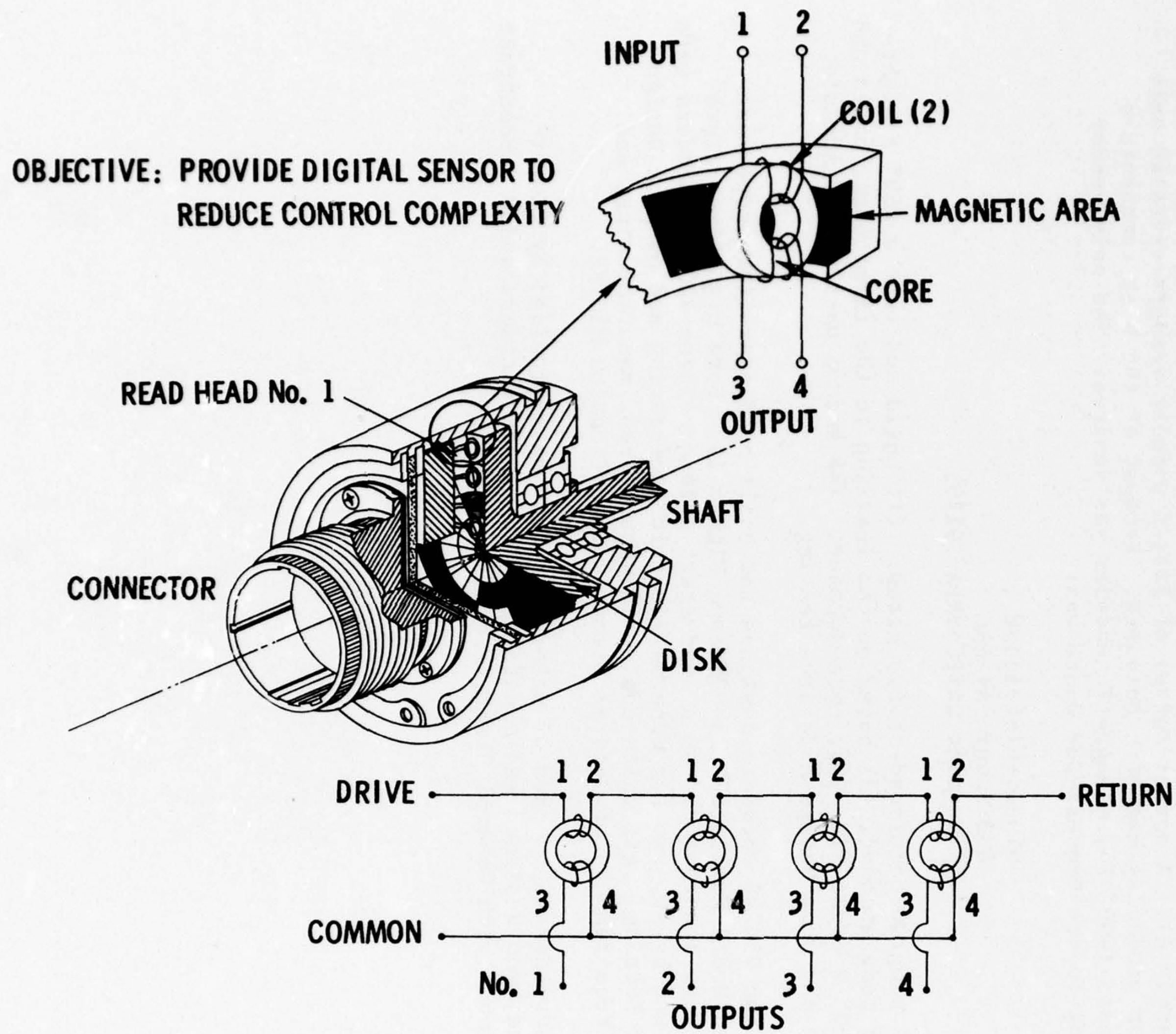


Figure 1. Magnetic Shaft Encoder.

4.0 DESCRIPTION OF OPERATION

A magnetic digital shaft encoder may be described as having a cylindrical housing with an electrical connector on one end and a coaxial input shaft on the other. Internally, a flat, concentric, barium ferrite disk is attached to the end of the shaft perpendicular to its axis. Facing the disk, in close proximity, is a radial row of small toroidal transformers mounted in the housing, lying in a single plane perpendicular to the plane of the disk, one transformer for each digital bit. On the disk, there are concentric, interrupted, magnetized tracks, one for each transformer. The transformers are excited in series by a 200 kHz sine wave current. The secondary windings are read individually with a common ground. See Figure 1.

When a magnetized portion of the disk is adjacent to a transformer, the core becomes saturated and creates no voltage in the secondary winding. This signal is called a "zero". As the magnetic spot moves away with shaft rotation, the core becomes unsaturated and produces a voltage in the secondary winding. This signal is called a "one". For a given shaft position, the transformers produce a unique pattern of "ones" and "zeros". An eight-bit (<u>eight</u> transformers in this case) encoder will identify 256 (two to the eighth power) positions of the shaft. A nine-bit encoder will identify 512 shaft positions.

The Gray code used has some very useful characteristics. It is an absolute code (i.e., knowledge of past history is not required to identify shaft position). Within the resolution of the encoder, each shaft position creates a unique digital output signal. In the transition from one shaft position to the next, only one bit at a time changes. There is therefore no need to synchronize simultaneous transitions, which is difficult to mechanize.

5.0 DESIGN DISCUSSION

5.1 REQUIREMENTS

The following requirements were established as being applicable to a digital shaft encoder:

Number of bits	Eight
Type of bit	Magnetic
Code	Gray code linear
Travel	360 degree continuous
Excitation	400 milliamps peak at 200 kHz
Accuracy	± One bit
Temperature	-65° to 400° F
Mounting	Servo-Type

The above requirements were incorporated in a General Electric specification HCD-1089B with two classes, A and B. Class A was for 400° F and Class B 250° F.

5.2 SHAFT ENCODER DESIGN

5.2.1 Magnetic Heads

The shaft encoder designed by Singer-Librascope has toroidal ferrite-core transformers for the magnetic heads. The cores are about 0.060 inch in diameter with a 0.030 inch inside diameter. With polyimide insulation, the primary and secondary windings on each core are wound with 39- and 44-gage copper magnet wire, respectively. Nickel-plated magnet wire was not considered necessary for 400° F. A high temperature adhesive is used to bond the cores to the ceramic head holder. The windings loop through the head holder to provide some mechanical restraint for the cores.

5.2.2 Head Holder

An aluminum oxide bar was precision ground to serve as a holder for the magnetic heads. The following requirements are necessary for the head holder:

1. Good rigidity

2. Good electrical insulator

3. Good dimensional stability

4. Good match on thermal expansion with the ferrite cores

5. Reasonable strength

6. Good bonding to ferrite cores and stainless steel mounting plate.

Aluminum oxide was selected as best in meeting all the requirements.

5.2.3 Disk and Shaft

Barium ferrite was used as the material for the disk. Eight concentric, interrupted, permanently magnetized tracks are programmed into the face of the disk by a machine specially designed for that purpose. The pattern of the magnetized and nonmagnetized sections of the tracks sets the Gray code characteristic of the encoder. Magnetized areas are relatively sharply defined to minimize cross talk and create a steep transition between "zeros" and "ones". Due to the brittle nature of barium ferrite and its notch sensitivity, it is not keyed to the shaft, but rather bonded to a hub on the shaft by a high temperature adhesive. The 50 inch-ounces of torsional strength achieved is considered adequate. Made of nonmagnetic stainless steel, the shaft is splined and threaded on the outboard end to permit positive engagement with the driving mechanism.

5.2.4 Bearings

Two R4 bearings provide the "wheelbase" for supporting the shaft and disk. Made of hardened 440-C stainless steel, the bearings are shielded to minimize entry of foreign particles. A bearing wavy washer provides a spring load to locate the disk axially, allow differential thermal expansion and provide a thrust preload on the bearings for improved vibration resistance.

5.2.5 Housing

Machined from 6061-T6 aluminum, the housing is cylindrical with a servo-type mounting. See Figure 2. Snap ring grooves are provided for retention of the head holder mounting plate and the end plate.

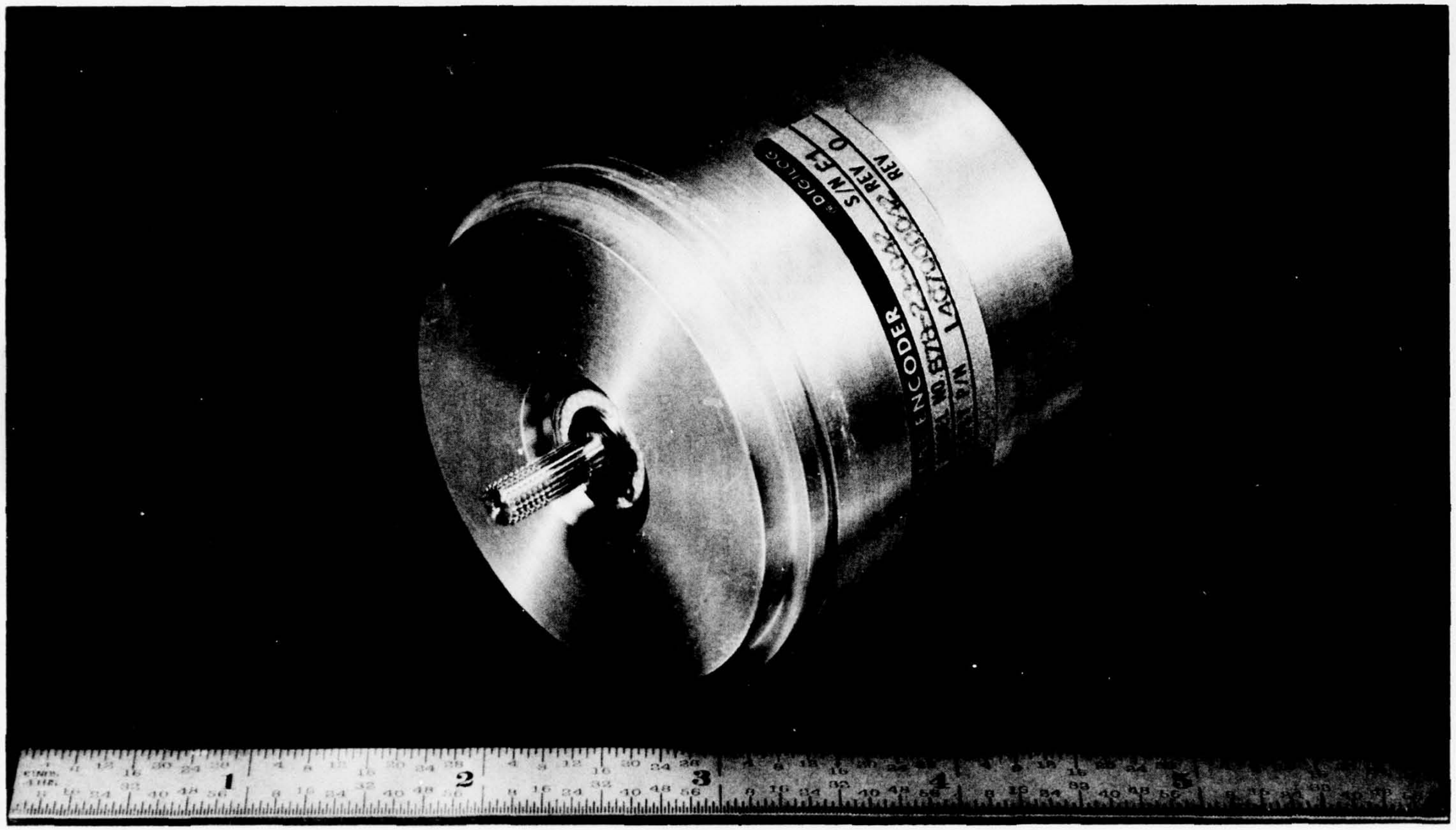


Figure 2. High Temperature Digital Shaft Encoder, Shaft End.

5.2.6 Plates

The two plates of the encoder are machined from stainless steel and aluminum. On the stainless steel mounting plate is located the bonded ceramic head holder (with magnetic heads) and glass-insulated feedthroughs for the magnet wire. A conformal coating protects the magnet wire from vibration and handling damage. Stranded lead wires on the opposite side of the mounting plate are soldered to the feed-throughs and connector with 588° F solidus solder and anchored to both plates. The connector is mounted on the aluminum end plate which is keyed to the housing to prevent rotation by cable connector torque. A small metal block which serves as the key also captures the tapered snap ring retaining the end plate. Radial taper on the two snap rings creates a wedging action to more positively locate the two plates in the axial direction. See Figure 3.

5.2.7 Connector

Mounted on the end plate, the connector is a NAS1599 hermetic type common to the F101 engine. A total of 12 pins leaves one spare.

5.2.8 Excitation

A 200 kHz sine wave current of 400 milliamps peak amplitude is used to excite the magnetic heads (transformers) in series. Current regulation permits heads to saturate without disturbing the output of the unsaturated ones. Using a 200 kHz excitation yields a high output signal (3 to 4 volts peak) and steep transitions for good readout accuracy. For comparison, normal excitation current for an LVDT is about 10 milliamps.

5.3 ELECTRICAL UNIT

This subsection describes the operation of the electrical unit which provides the excitation and readout of the digital shaft encoder.

5.3.1 Hardware Description

Shown in Figure 4 is the circuitry of the electrical unit receiver boards. The output waveform of the encoder is a narrow pulse, occurring when the ferrite core for that bit is driven from saturation in one direction to the other by the excitation current. Switching is inhibited by the presence of a magnetized section of the encoder disk. The transition from a full amplitude pulse, representing a "one", to a "zero" pulse level requires approximately two degrees of shaft rotation. This is greater than the resolution of an eight bit encoder. To extract the maximum resolution, a threshold is set at one-half the maximum output of the bit line which creates a threshold of two volts. Devices IC1 through IC4 of Figure 4 are dual differential line receivers consisting of a comparator and a NAND

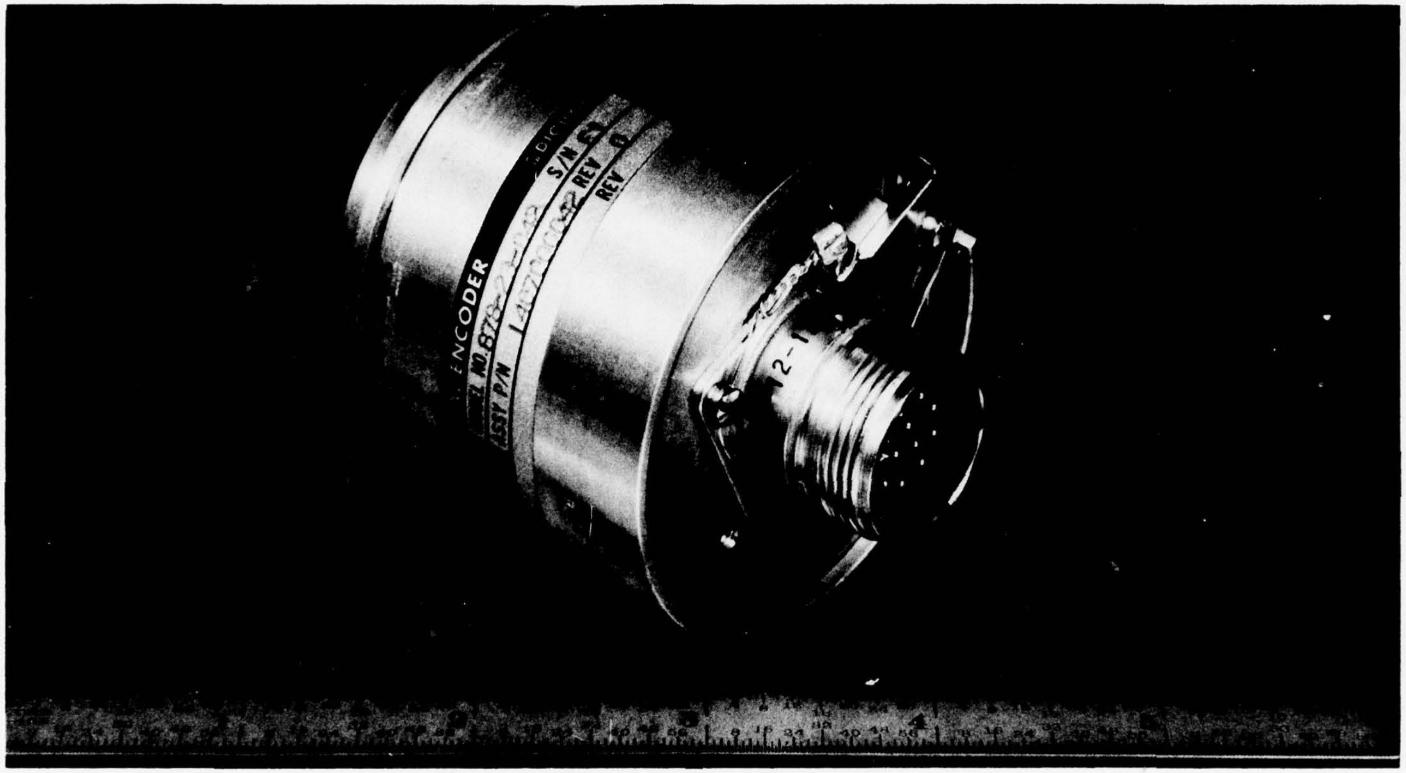


Figure 3. High Temperature Digital Shaft Encoder, Connector End.

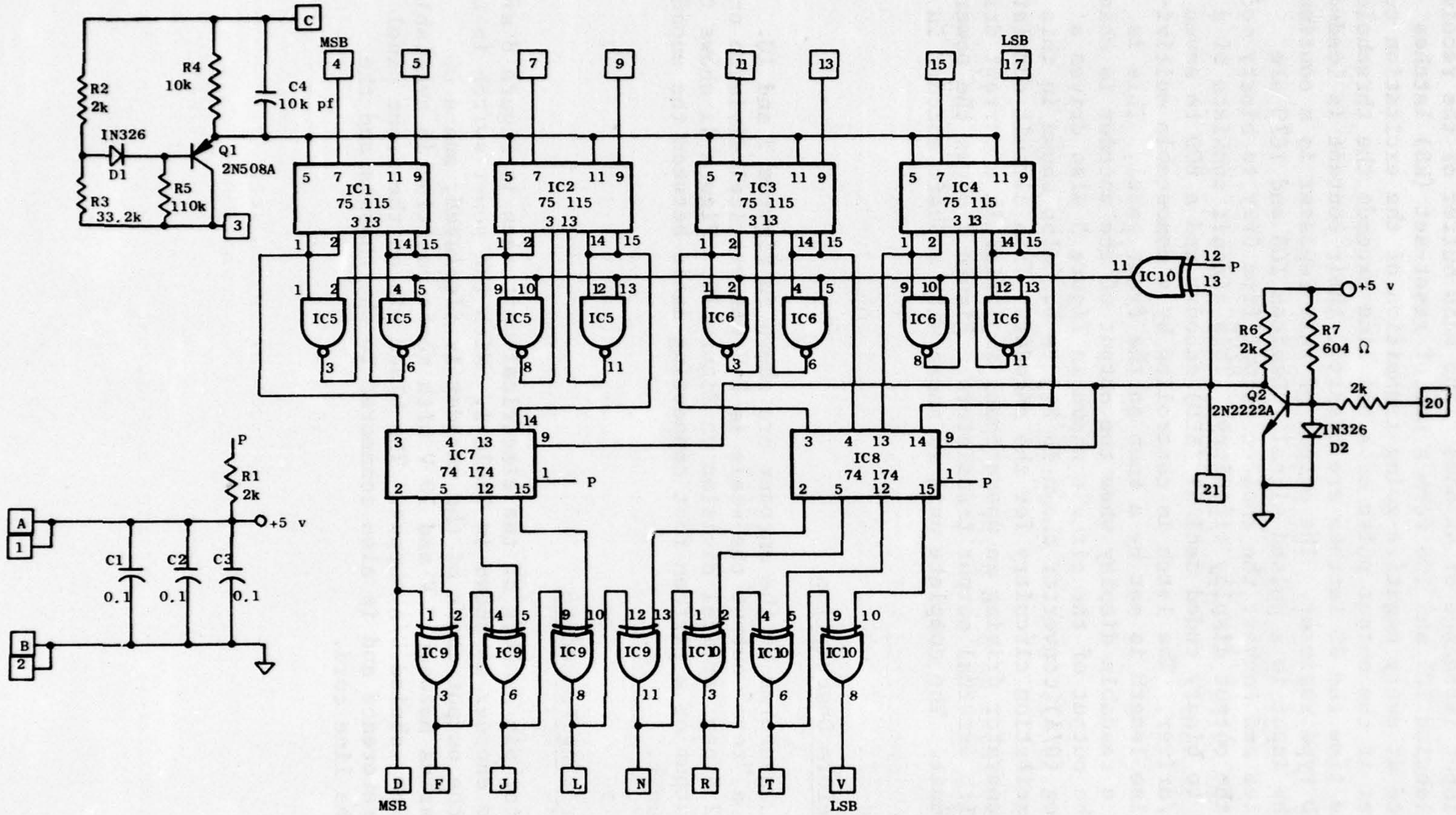


Figure 4. Magnetic Shaft Encoder Receiver Board.

buffer with an input impedance of 4K ohms. The NAND buffer of the receivers and the NAND's labeled IC5 and IC6 form a set of reset-set (RS) latches which are cleared at every negative-going transition of the excitation current, and are set if the output pulse of a bit line exceeds the threshold voltage. At the time the RS latches are cleared, their content is loaded into a clocked D type register. The output of this register is a continuous logic signal; the input is a pulsed signal. Devices IC8 and IC10 are exclusive OR gates and convert the encoder output from Gray to binary code. Figure 5 shows the output display circuitry. This circuit consists of a latch, a binary to binary coded decimal (BCD) decoder and a BCD to seven segment decoder/driver. The latch is controlled by a monostable multivibrator whose pulse length is set by a knob on the front panel. This is done to provide a readable display when the output of the encoder is changing rapidly. The output of the circuit shown in Figure 5 also drives a digital-to-analog (D/A) converter shown in Figure 6. Also shown in this figure is the excitation circuitry for the encoder. This circuit consists of a function generator driving an operational amplifier in a current drive configuration with external output transistors. Figure 7 shows the power supply for the unit. The complete unit is shown with a shaft encoder in Figure 8.

5.3.2 Waveform Description

The output waveforms of the encoder are shown in Figures 9 and 10. For a "one" and a "zero" output the scale is 2 V per vertical division on Figure 9 and 0.2 V per vertical division on Figure 10. Figure 11 shows the effect on the output of a fifteen foot connecting cable between the encoder and electrical unit.

5.3.3 Operating Procedure

The connector pin numbers of the electrical unit seen in Figure 8 are connected to the encoder as shown in Table 1. With the power switch in the "ON" position, the output count of the encoder is displayed, and a DC voltage which varies between 0 V and 10 V with shaft position is available at the output pins labeled D/A output. The black pin on the front panel is the D/A output reference and is also connected to the chassis and the ground pin of the line cord.

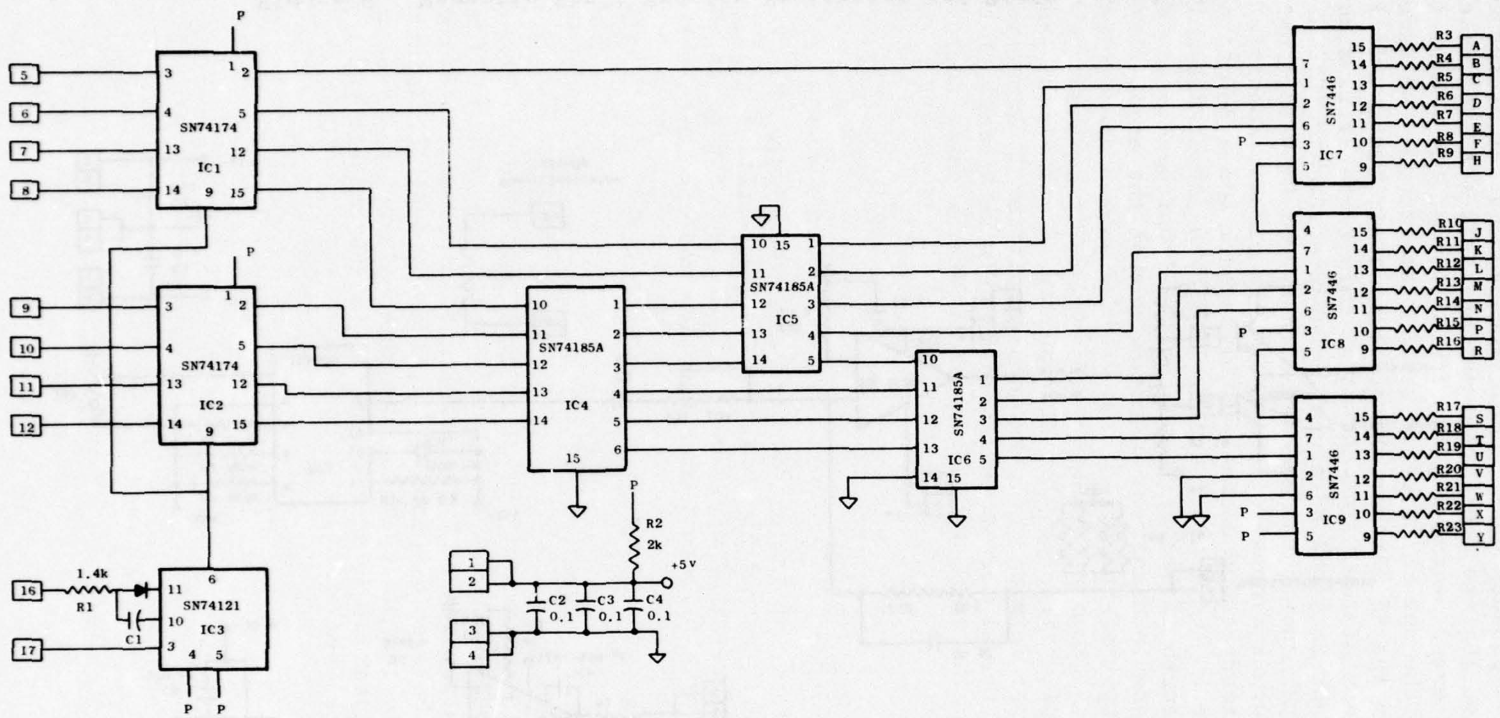


Figure 5. Magnetic Shaft Encoder Display Driver.

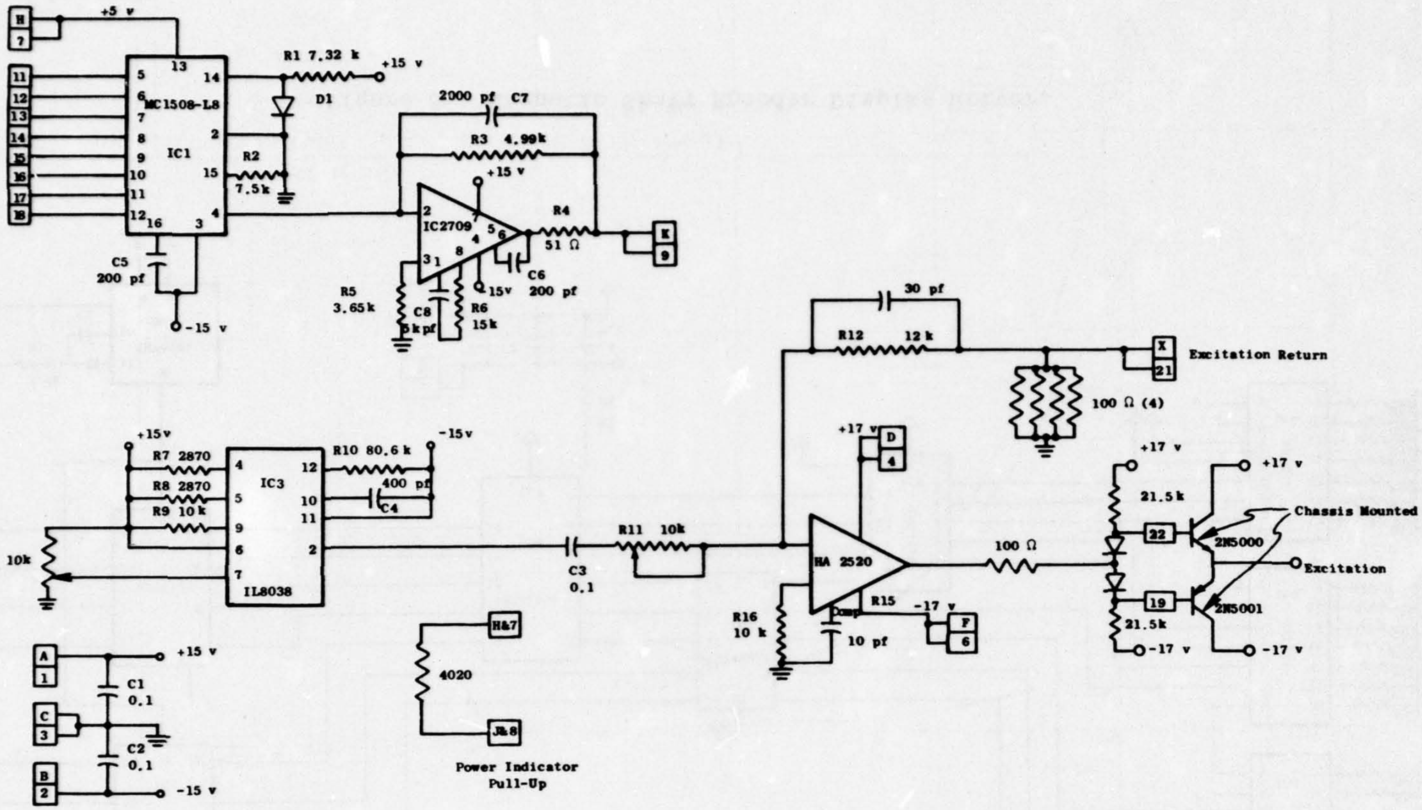


Figure 6. Magnetic Shaft Encoder Excitation and Digital-to-Analog.

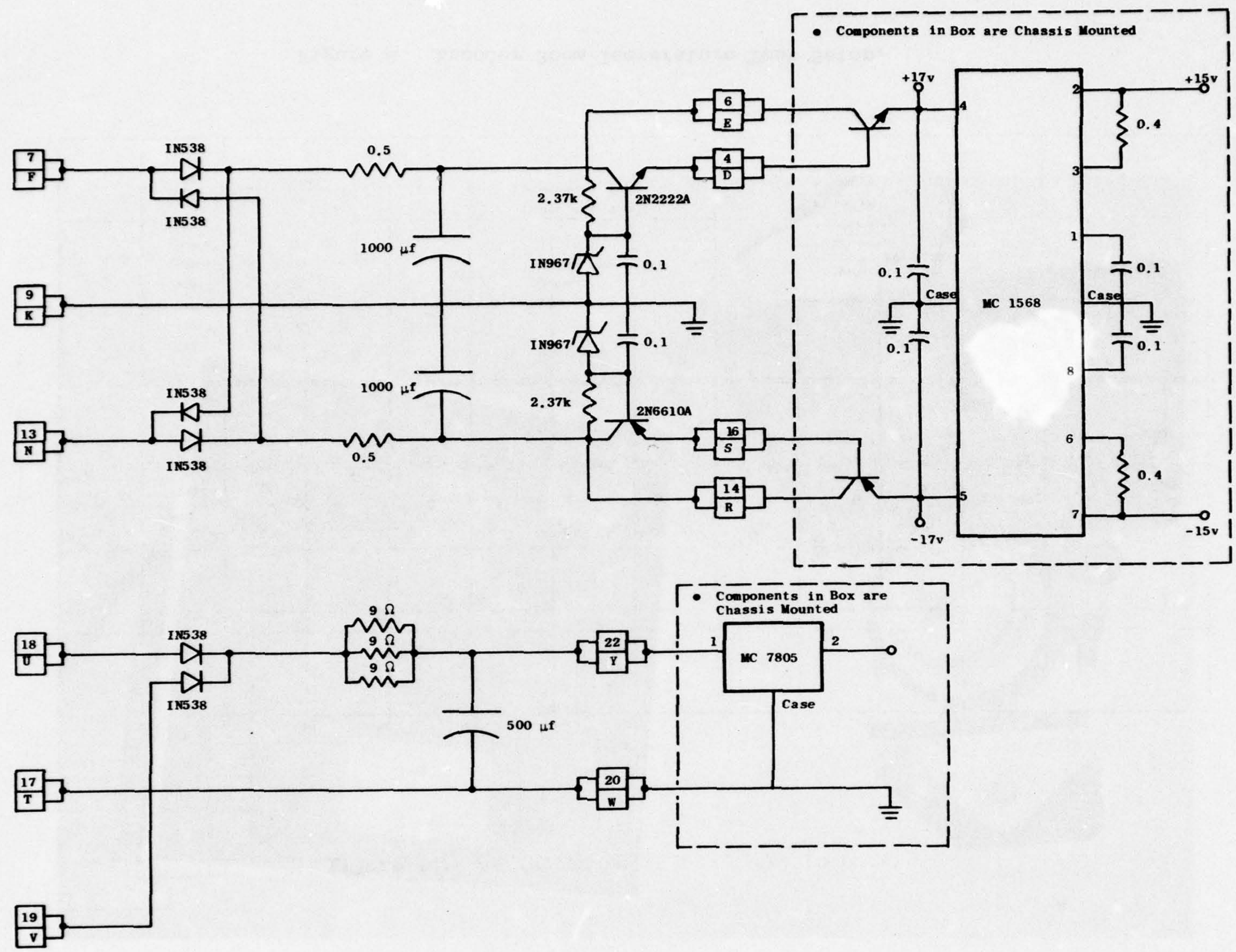


Figure 7. Magnetic Shaft Encoder Power Supply.

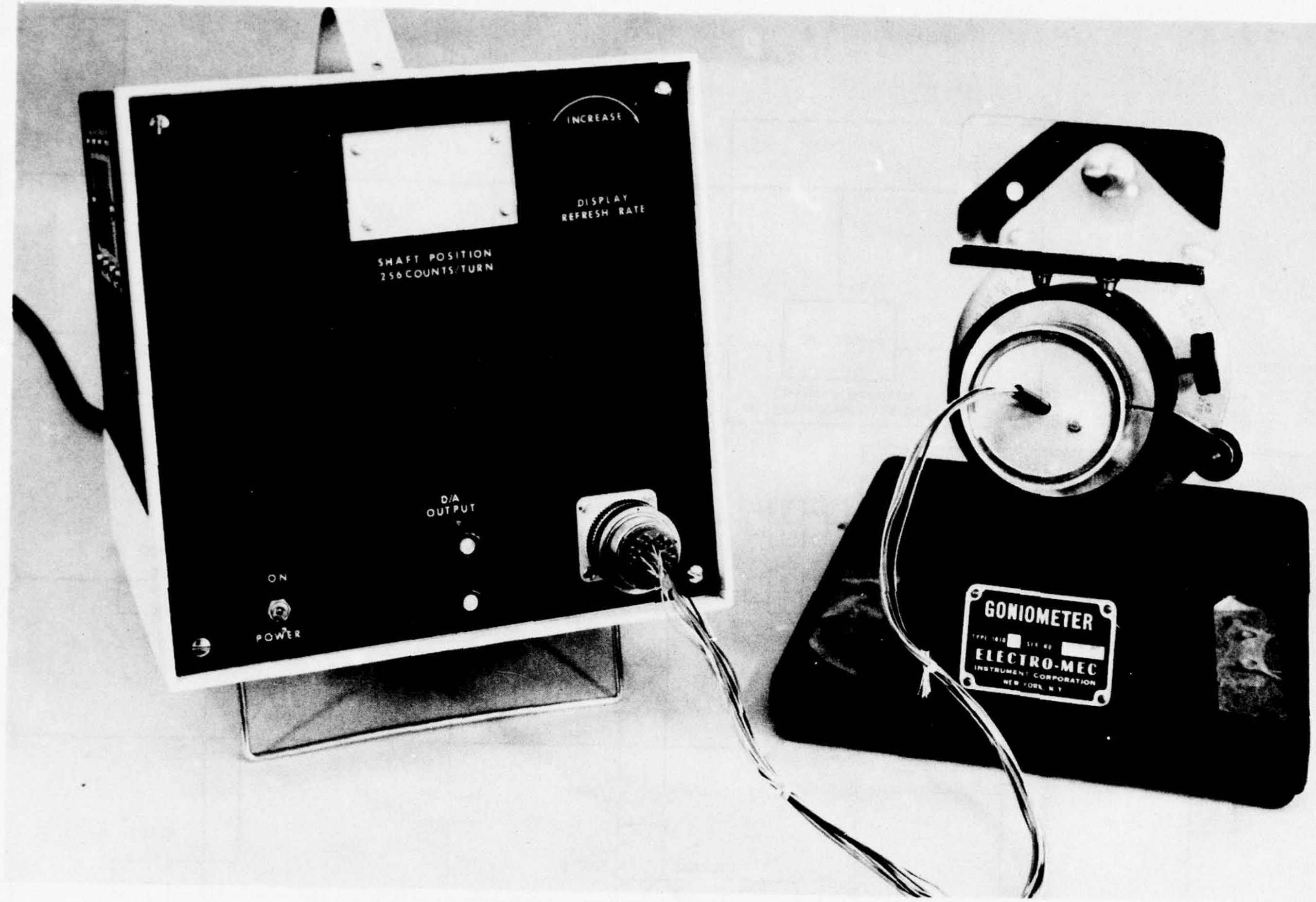


Figure 8. Encoder Room Temperature Test Setup.

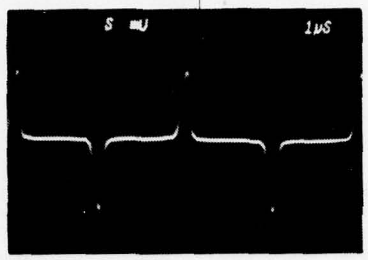


Figure 9. Waveform of "One" with Three-Foot Cable.

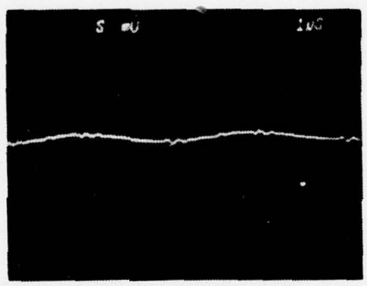


Figure 10. Waveform of "Zero".

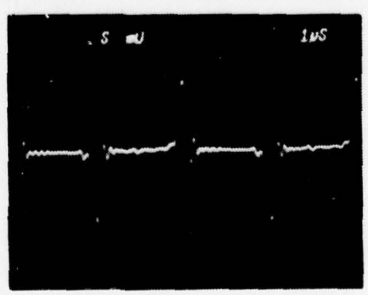


Figure 11. Waveform of "One" with 15-Foot Cable.

Table 1. Pin Number to Encoder Functions.

Connector Pin Number	Encoder Function	400° Encoder Pin Number
1	2^0 LSB	1
2	2^1	2
3	2^2	3
4	2^3	4
5	2^4	5
6	2^5	6
7	2^6	7
8	2^7 MSB	8
9	Signal GND	11
10	Excitation	10
11	Excitation Return	9

6.0 TESTING

6.1 PERFORMANCE TESTS

Testing at the General Electric Company was done in the Electrical Laboratory in Building 700. Figure 8 shows the room temperature setup using the specially designed hardware described in the previous paragraph. Tests were conducted at -65° F, room temperature, 250° F and 400° F.

6.1.1 Test Results

The accuracy requirement of plus or minus one bit was met at -65° F, room temperature, and 250° F, but not at 400° F, on the unit tested.

A maximum "zero" output requirement of 0.40 V half amplitude was met over the whole temperature range of -65° F to 400° F. See Figure 12.

A minimum "one" output requirement of 2.8 V half amplitude was met at -65° F, room temperature and 250° F, but not at 400° F. All bits fell short of the 2.8 V requirement. See Figure 12.

6.1.2 Discussion of Data and Results

6.1.2.1 Saturation Effects

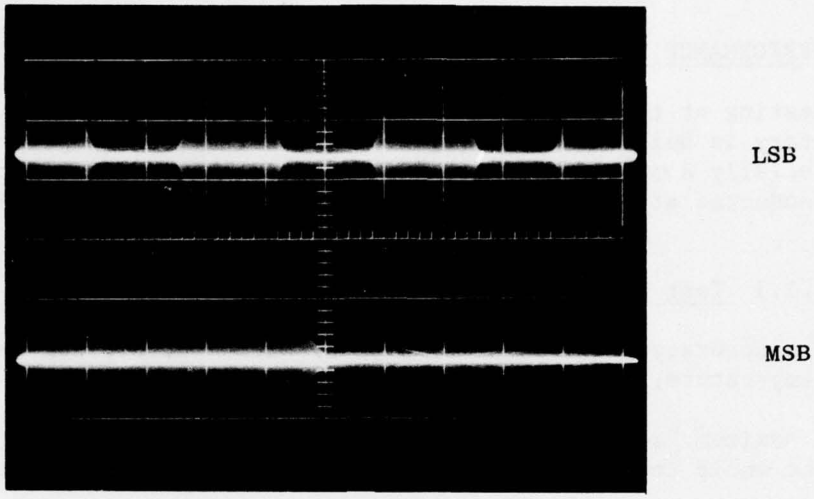
In general, the encoder performed as expected except at 400° F. The "ones" did not meet the minimum amplitude requirement and the broadening of the "zeros" caused some bits to fall out of limits on the accuracy requirements. Decreasing saturation flux density and permeability with increasing temperature were the prime factors for the problems. For a transformer:

$$E = -N \frac{d\phi}{dt} \times 10^{-8} = -N \left(\frac{dI}{dt}\right)\left(\frac{d\phi}{dI}\right) \times 10^{-8}$$

where

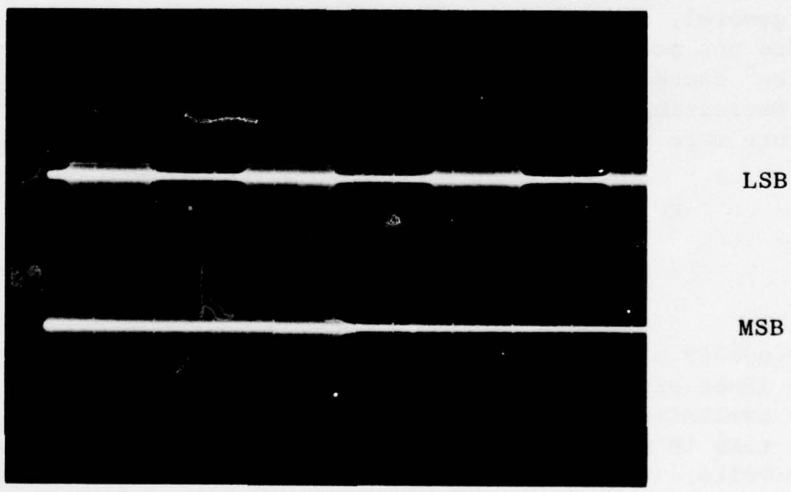
N = number of turns in secondary winding
ϕ = lines of magnetic flux in Maxwells
I = excitation current in amperes
t = time in seconds
E = volts

The term dI/dt depends on the maximum current (I_m) amplitude and the excitation frequency (f).



Room Temperature

- 2.0 volts/cm
- 600 rpm
- 0.5 ms/cm



400° F

Figure 12. Temperature Effect on Encoder Output.

$$I = I_m \sin \omega t$$

$$\frac{dI}{dt} = I_m \omega \cos \omega t$$

$$\omega = 2\pi f$$

For a typical configuration, $d\emptyset/dI$ is proportional to the permeability of the core material. Using a sine wave excitation, dI/dt is nearly constant up to $I_m/2$ so that peak output in a saturating transformer occurs at maximum permeability of the core. Therefore, a reduced peak output voltage indicates a loss of permeability. Note that at saturation, $d\emptyset/dI$ goes to zero making E zero. Reducing the saturation flux density by temperature has a twofold effect on accuracy. For the same magnetic field created by the tracks on the disk, the transformer must be farther from the magnetized spot before it begins to come out of saturation (broadening of "zeros"). As the distance to a disk magnetic spot increases, the gradient of the magnetic field decreases, reducing the slope of the transition voltage (volts versus shaft rotation), thereby delaying the attainment of the threshold voltage and broadening the zeros even further. Note in Figure 13 that the "zeros" begin to broaden very rapidly above 250° F. A curious characteristic was noted; the three most significant bits (MSB, MSB-1, MSB-2) showed a much larger temperature effect than the others.

6.1.2.2 Interpolation Difficulties

Digital devices have a unique characteristic not generally found in analog devices. Because of the smooth, continuous nature of analog devices, when any two adjacent points are in limits, any points in between will probably be in limits. This is not true for digital devices. Taking three consecutive points as an example: the two outboard points can be in limits, but the point in the middle may or may not be in limits. The two adjacent points apply no constraint on the one in the middle. Therefore, to make a positive statement about all digital counts being in limits, each one of them must be checked. Figures 14 and 15 show the results of such tests. An automated procedure for this test would be very useful. Included in the room temperature data are some 400° F points in Figure 14, three of which fell outside the accuracy limits. At room temperature, MSB-2 showed the largest deviation.

6.1.2.3 Temperature Effects

Figures 16, 17, 18, and 19 show the effect of temperature on the transitions of the three most significant bits. The broadening of the "zeros", the reduced amplitude of the "ones" and the reduced transition slopes at 400° F are clearly visible. In Figure 12, test data from Singer-Librascope show oscilloscope traces with the effect of 400° F on the output of LSB and MSB. Characteristics similar to those mentioned in the previous paragraph are apparent.

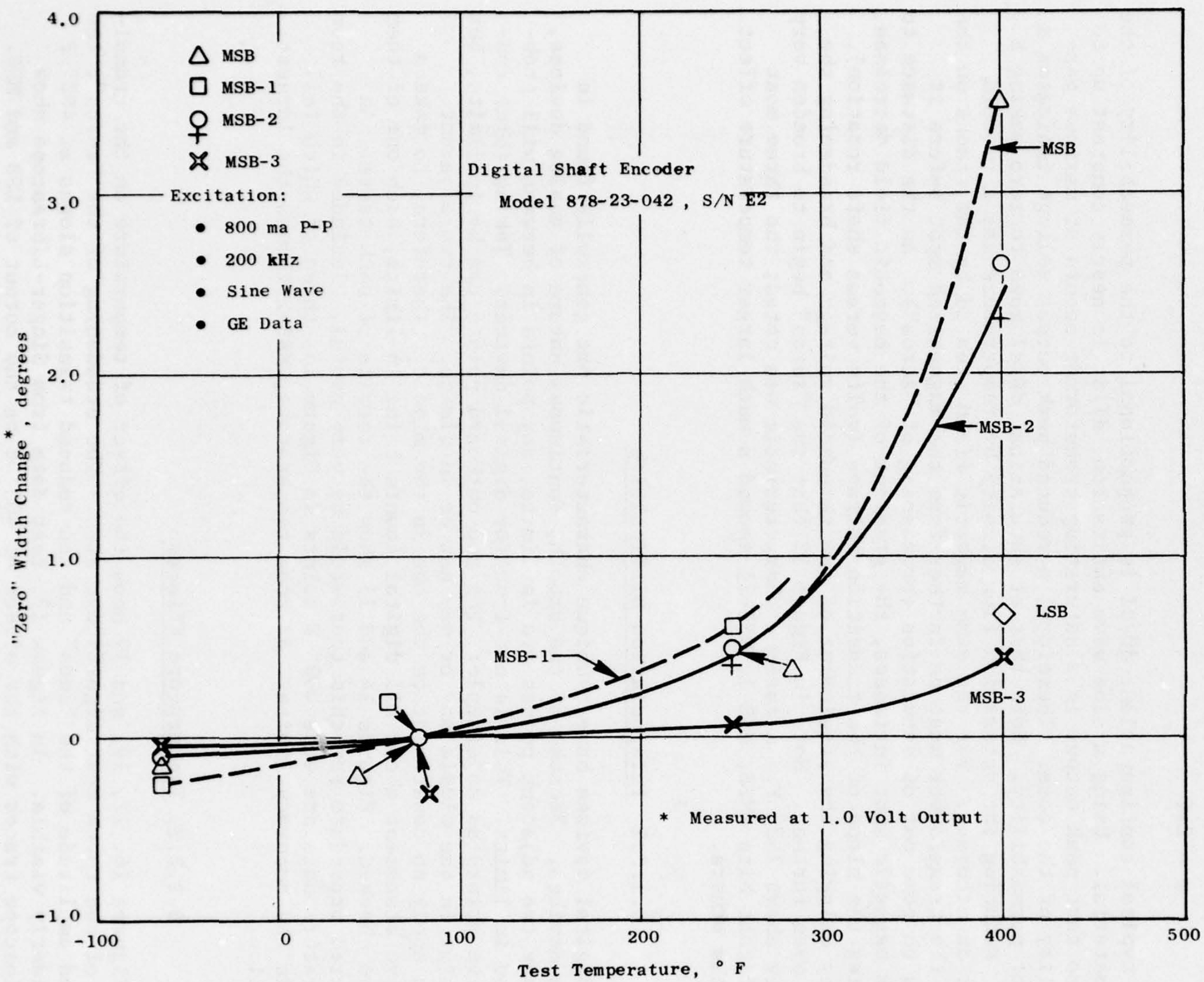


Figure 13. Temperature Effect on "Zero" Width.

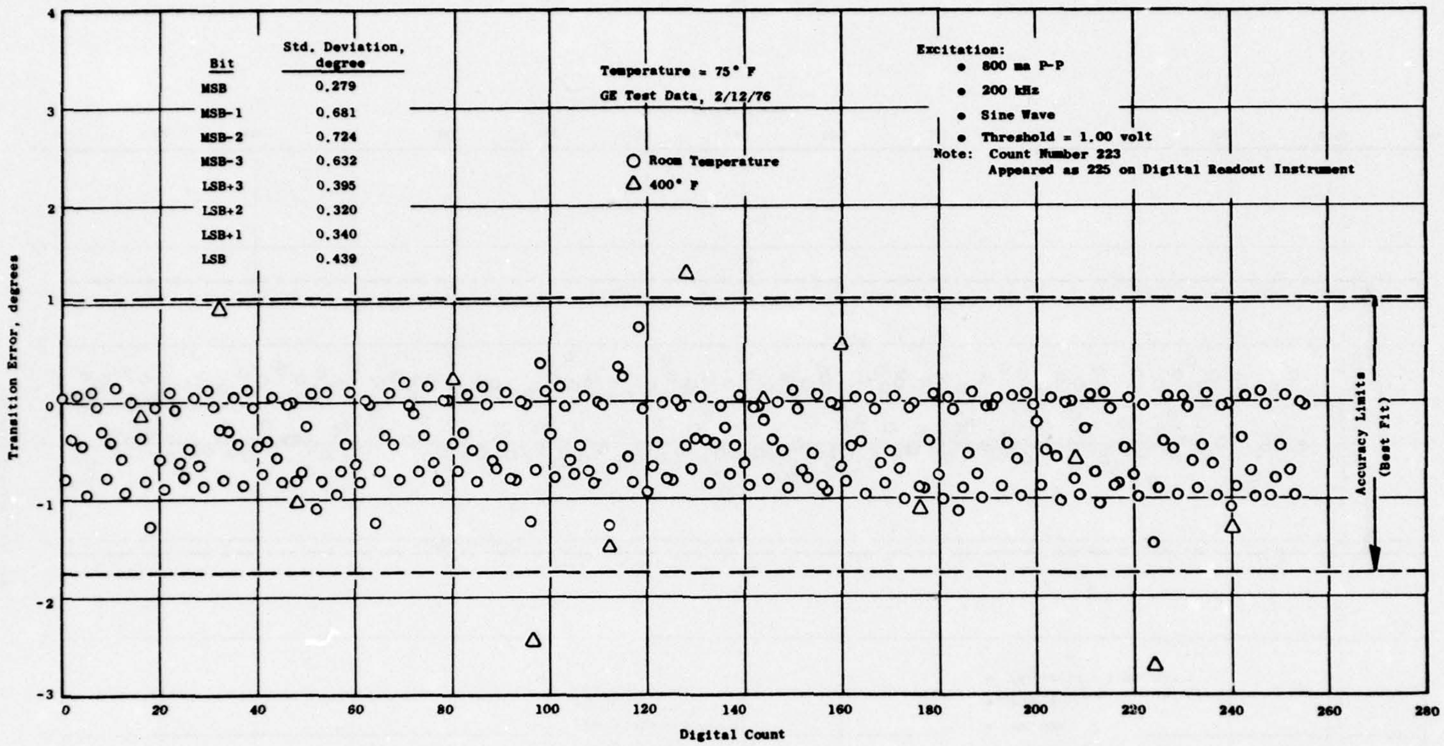


Figure 14. Deviation Chart for Shaft Encoder.

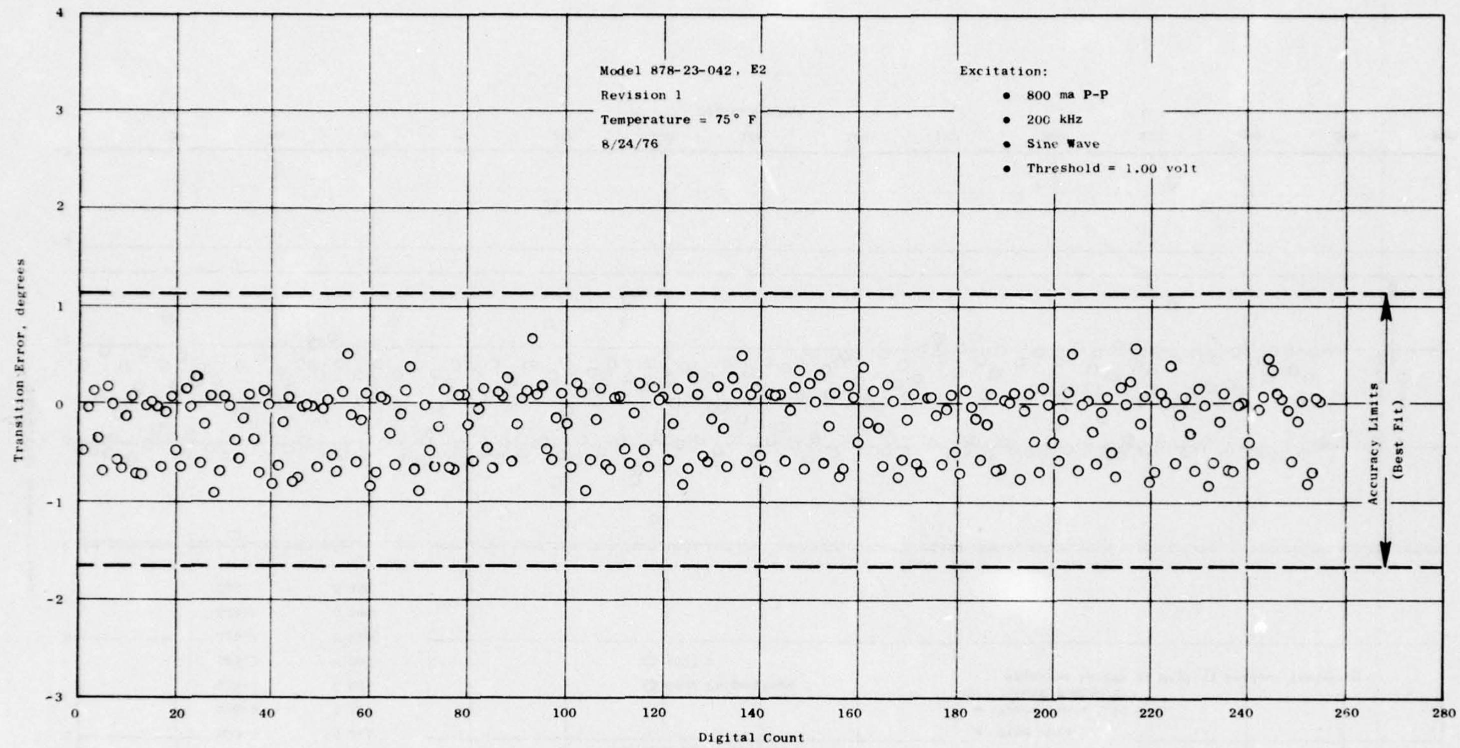


Figure 15. Deviation Chart for Revised Shaft Encoder.

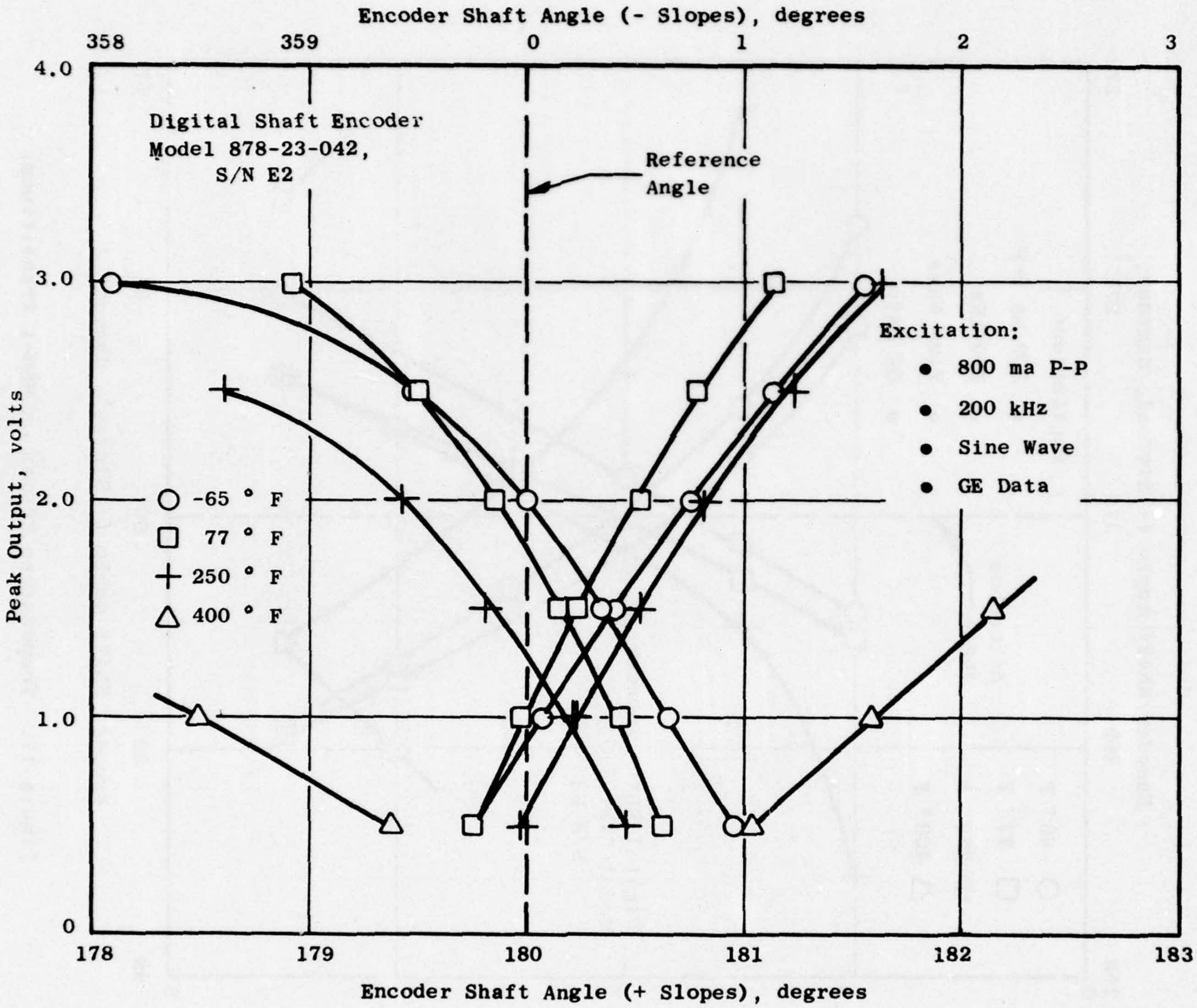


Figure 16. Temperature Effect on MSB Transitions.

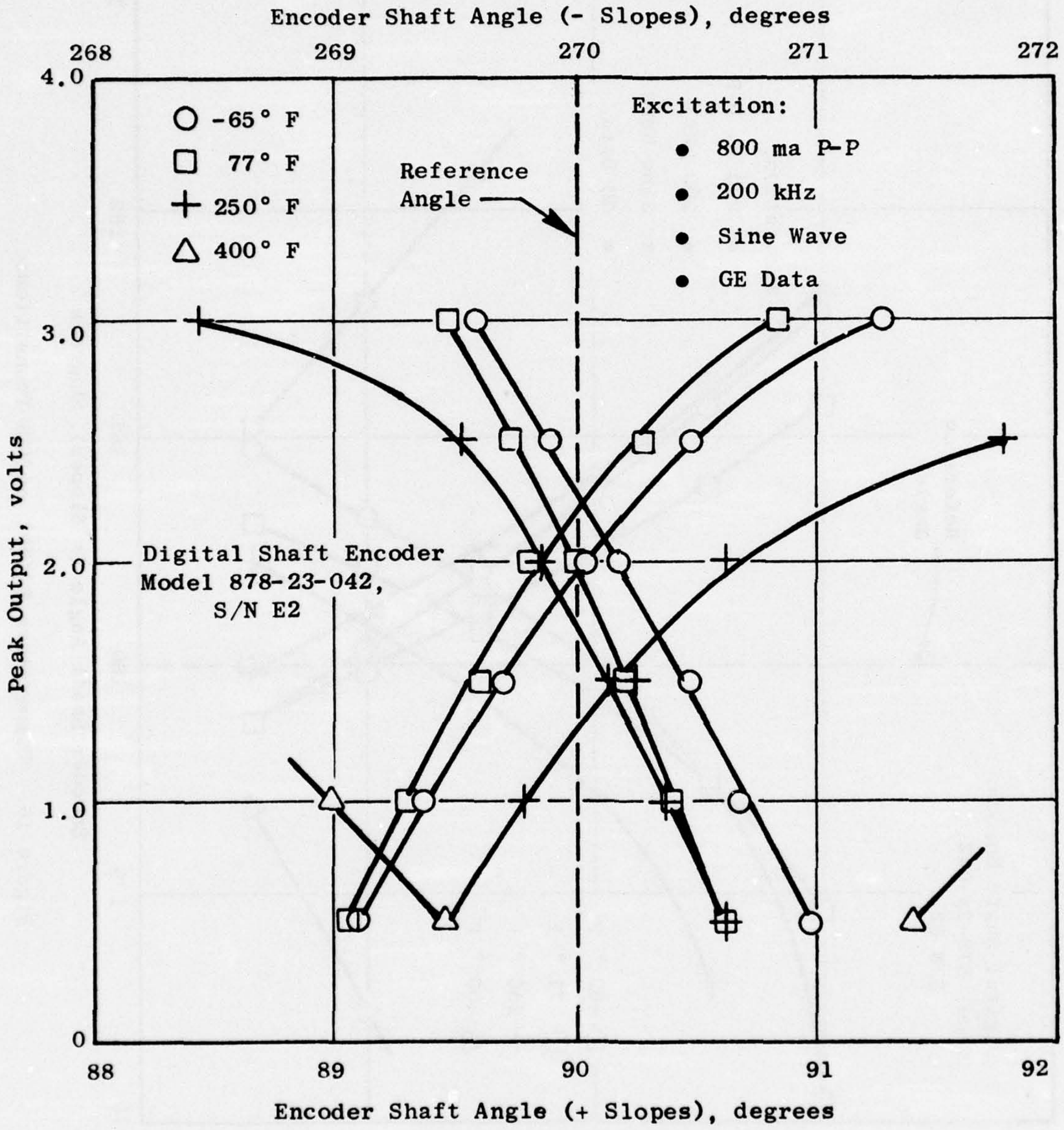


Figure 17. Temperature Effect on MSB-1 Transitions.

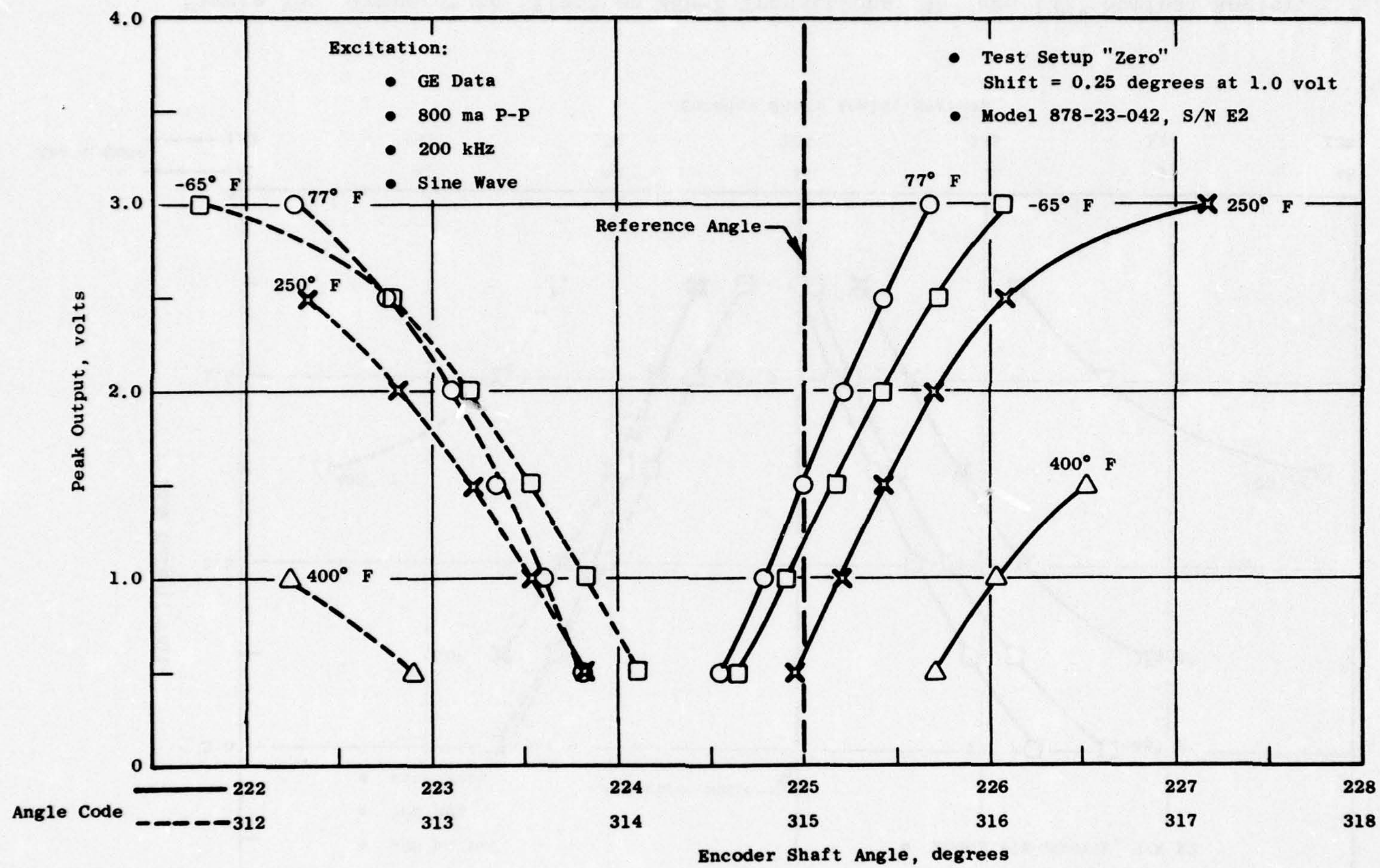


Figure 18. Temperature Effect on MSB-2 Transitions, 225° and 315° Nominal Angles.

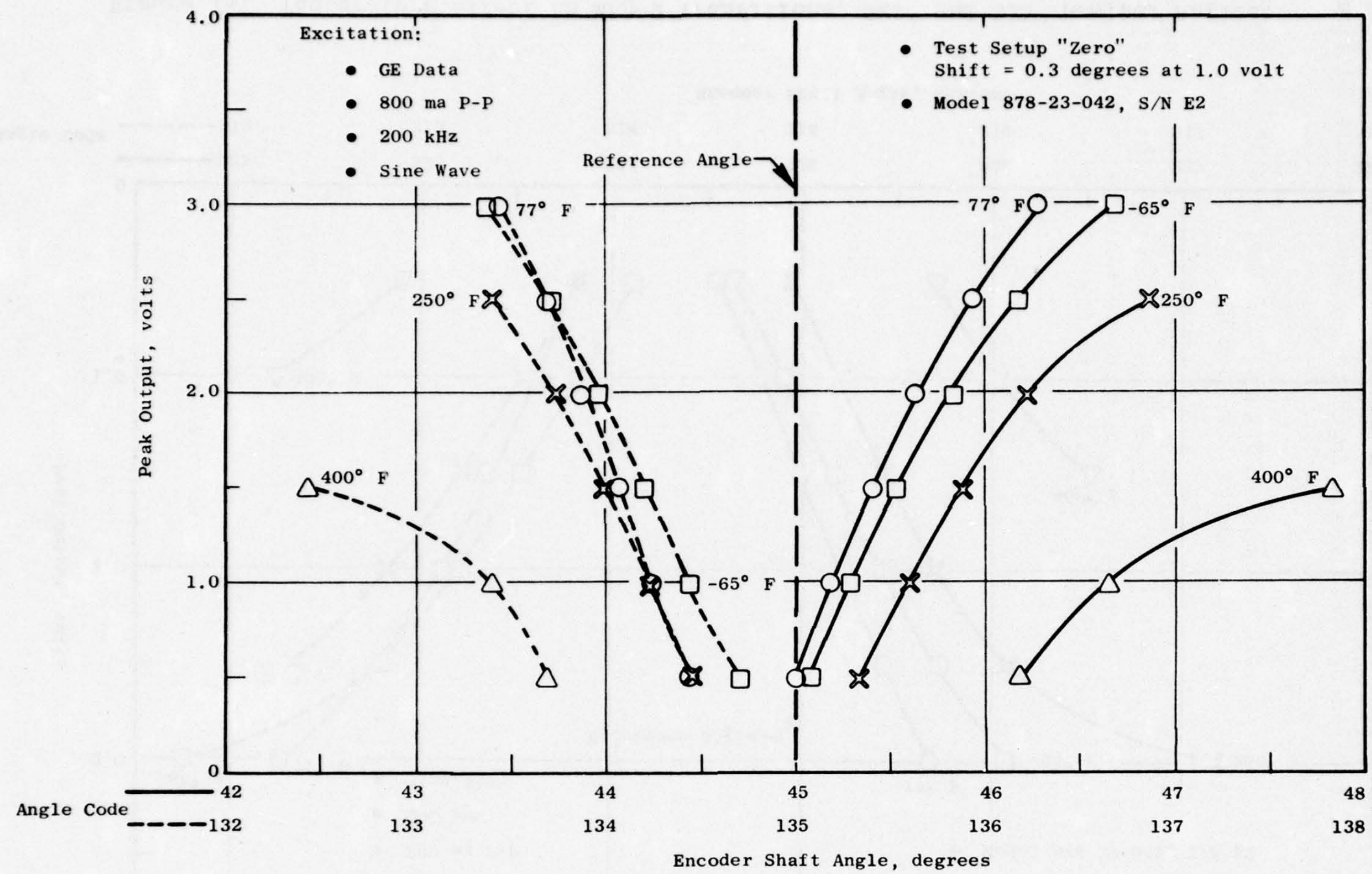


Figure 19. Temperature Effect on MSB-2 Transitions, 45° and 135° Nominal Angles.

6.1.2.4 Excitation Frequency Effect on Output

Early in the program the excitation frequency was to be 50 kHz. At the recommendation of the vendor, this was changed to 200 kHz. Figure 20 shows the increase in output signal.

Data from Singer-Librascope shown in Figure 21 illustrate the waveform of the output signal and the amplitude of the "zeros".

Since completion of their contracted work, Singer-Librascope has acquired some ferrite cores with substantially better high temperature characteristics. Preliminary testing to 375° F shows a very flat characteristic (very little temperature effect). This material looks very promising for a follow-up development program.

6.2 DESIGN ASSURANCE TESTS

Singer-Librascope conducted an Environmental Test in which a 400° F digital shaft encoder was subjected to thermal cycling, vibration, and life testing. These tests were conducted by the vendor in Glendale, California for the General Electric Company.

Thermal cycling of the digital shaft encoder was conducted per General Electric Specification HCD-1089B. Due to a misinterpretation of the requirements, the low temperature of thermal cycling was set at -65° C instead of -55° C. After the encoder failed in three attempts, the low temperature point was corrected and a thermal barrier added to reduce the thermal stresses in the ferrite transformers. Thirty cycles were subsequently completed with only a bad solder joint causing a malfunction. A functional check was conducted after each 10 thermal cycles (-65° F to 400° F).

A total of three vibration tests were conducted per paragraph 4.3.1.1 of General Electric Specification HCD-1089B. In the first test, a ferrite core was broken by the wedging of an aluminum chip between the core and disc. This aluminum chip came from one of the snap ring grooves in the housing. A correction was made by ultrasonic cleaning the housing prior to assembly.

Following the second vibration test, ferrite dust particles were observed inside the encoder. This was caused by unsupported loops of the primary windings abrading the inside diameter of the cores, creating ferrite dust. See Figures 22 and 23.

Corrections applied to resolve the problem were:

1. Reducing the primary winding wire size
2. Reversing the coil winding direction
3. Improved potting of the wires to prevent abrasion of the cores.

In this configuration (See Figures 24 and 25), the vibration test was completed with no discrepancies noted.

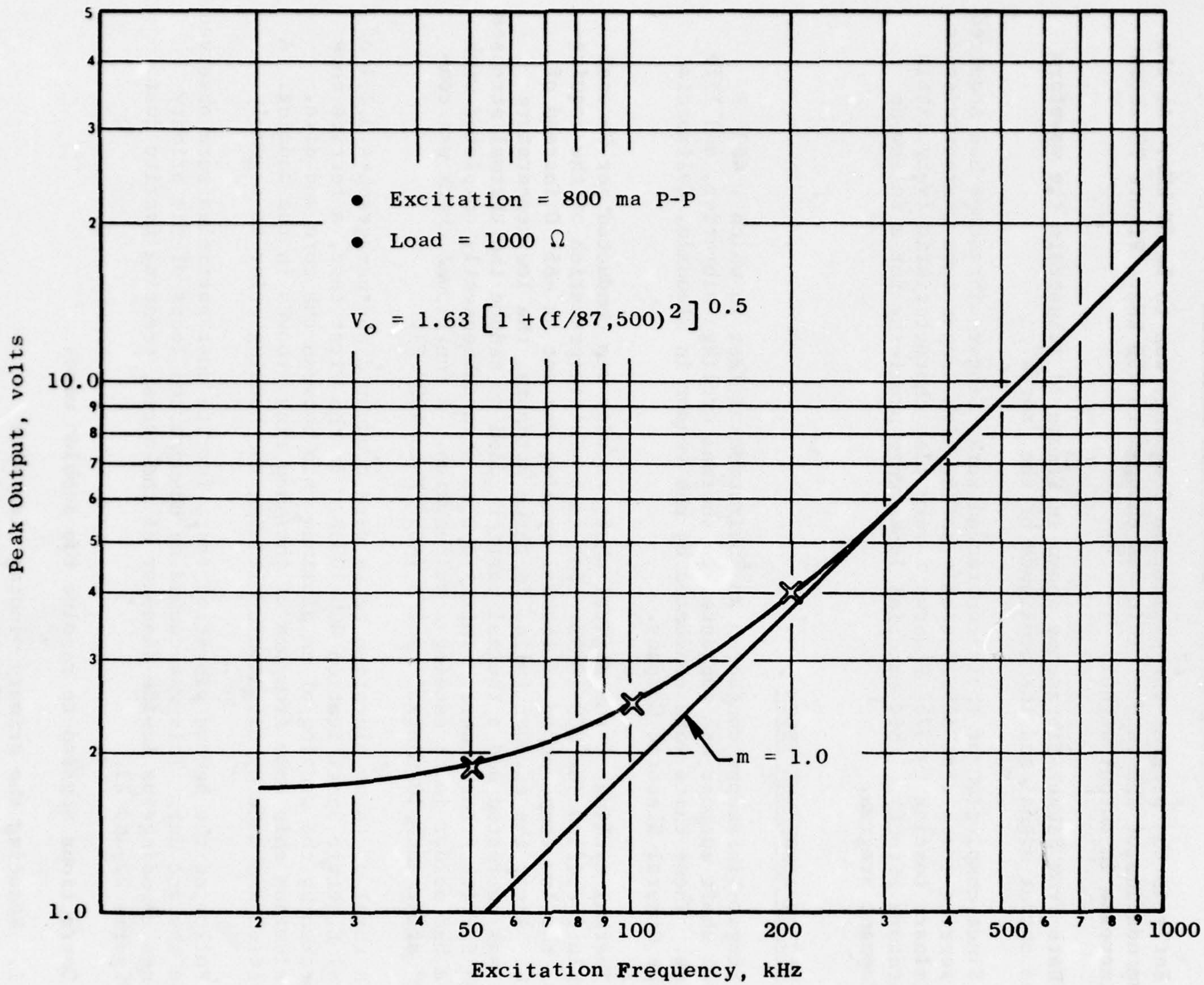
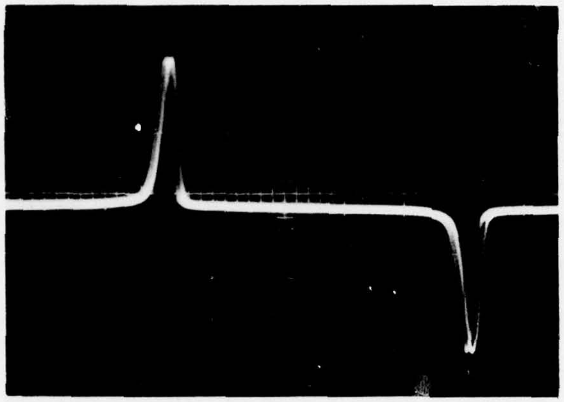


Figure 20. Effect of Excitation on Encoder Output.

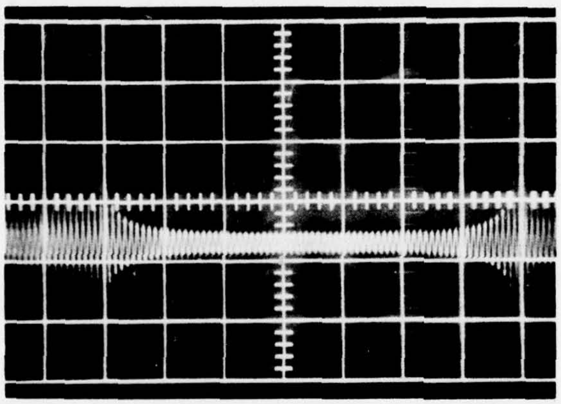


LSB "One"

1.0 volt/cm

1.0 μ sec/cm

Excitation: 100 kHz

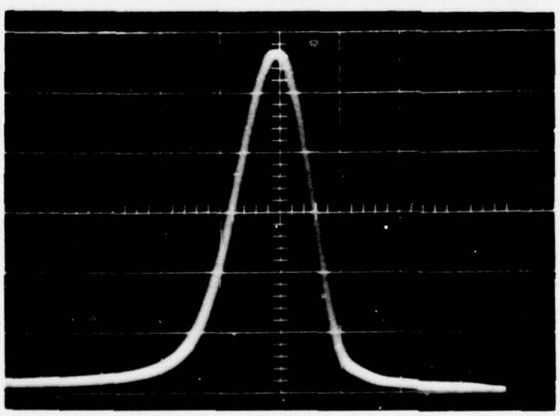


LSB "Zero"

200 mv/cm

0.1 ms/cm

Excitation: 100 kHz



MSB "One"

0.5 v/cm

200 ns/cm

Figure 21. Room Temperature Test, "Zero" and "One".

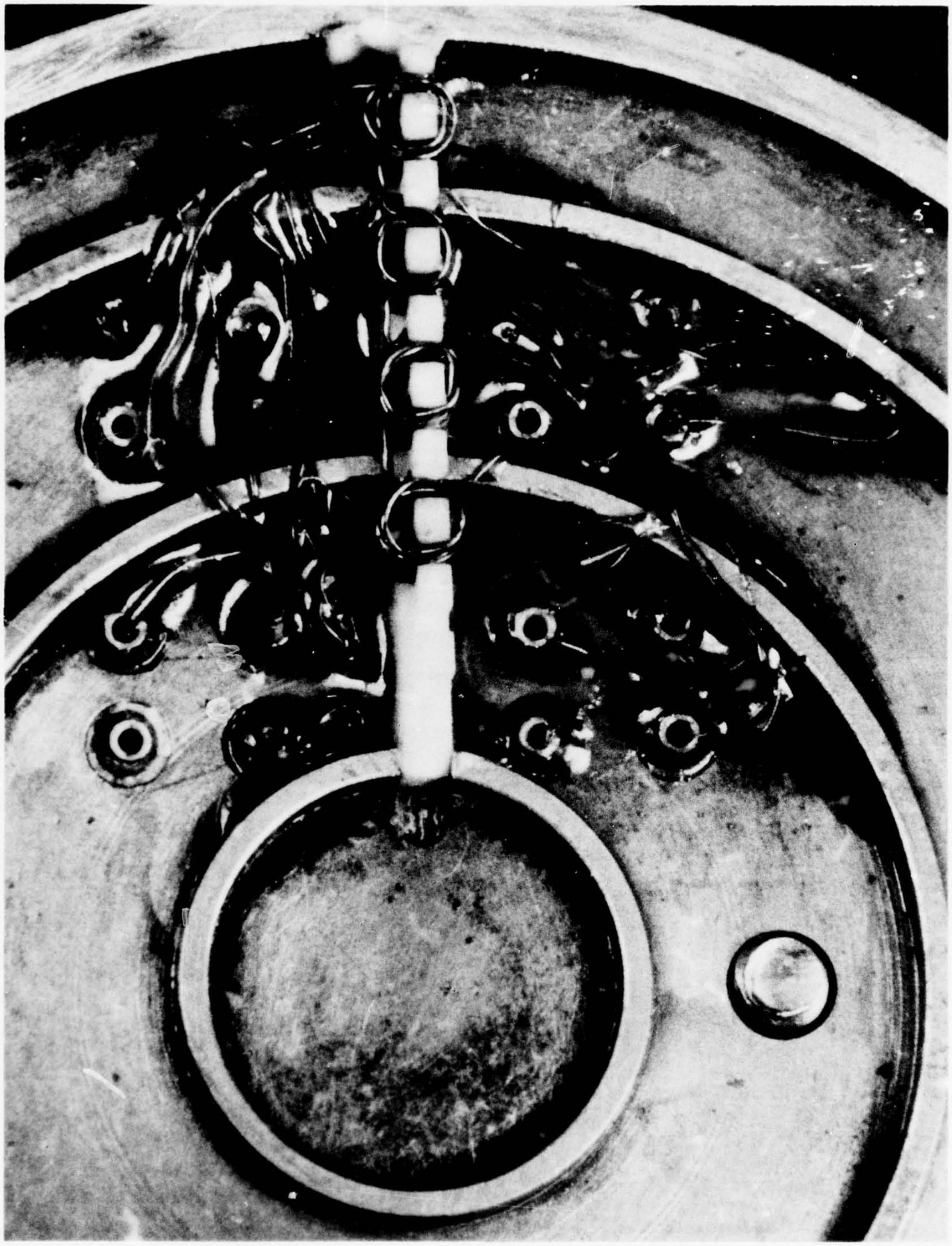


Figure 22. Vibration Failure (Magnification: 7.3 ×).

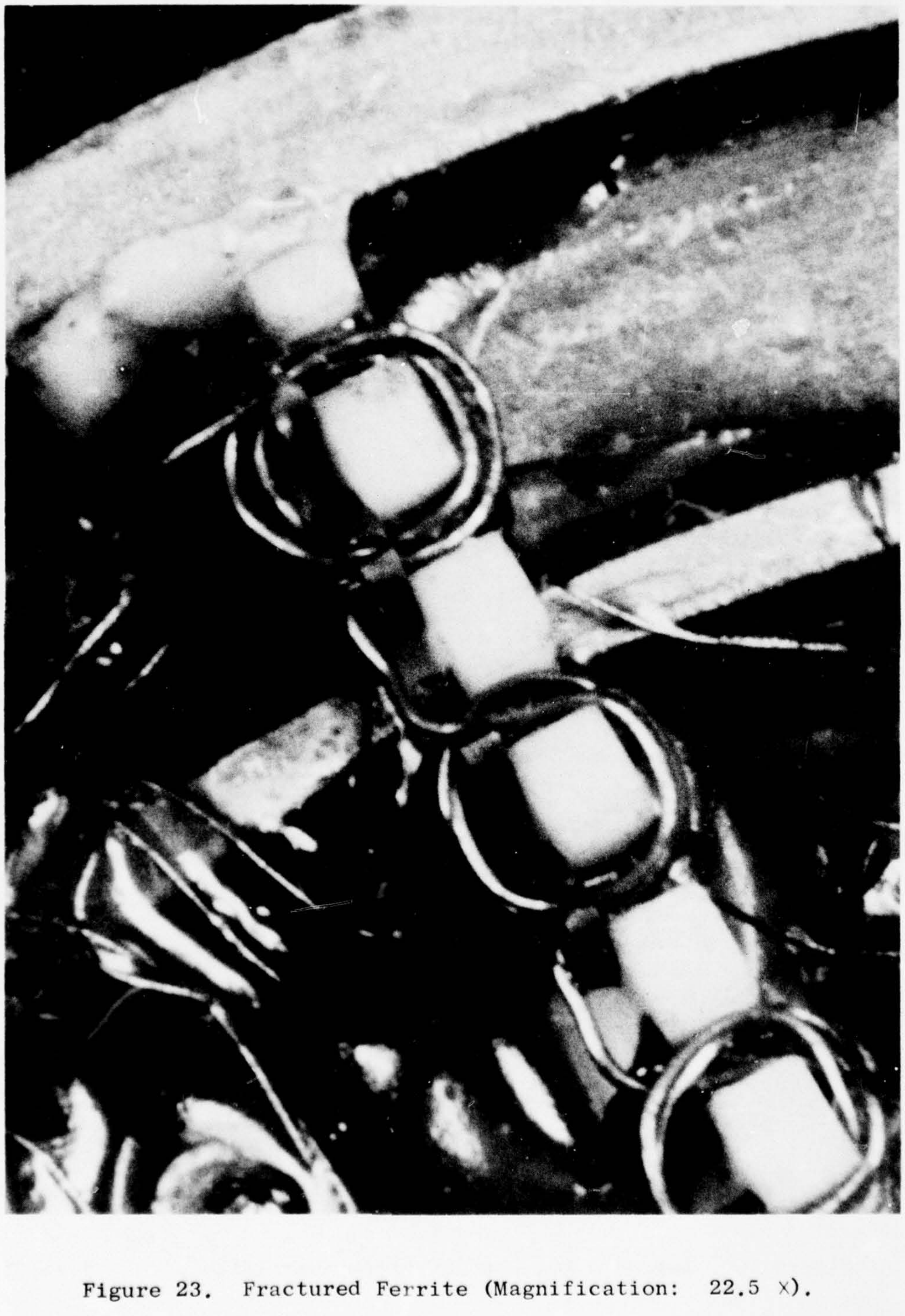


Figure 23. Fractured Ferrite (Magnification: 22.5 x).

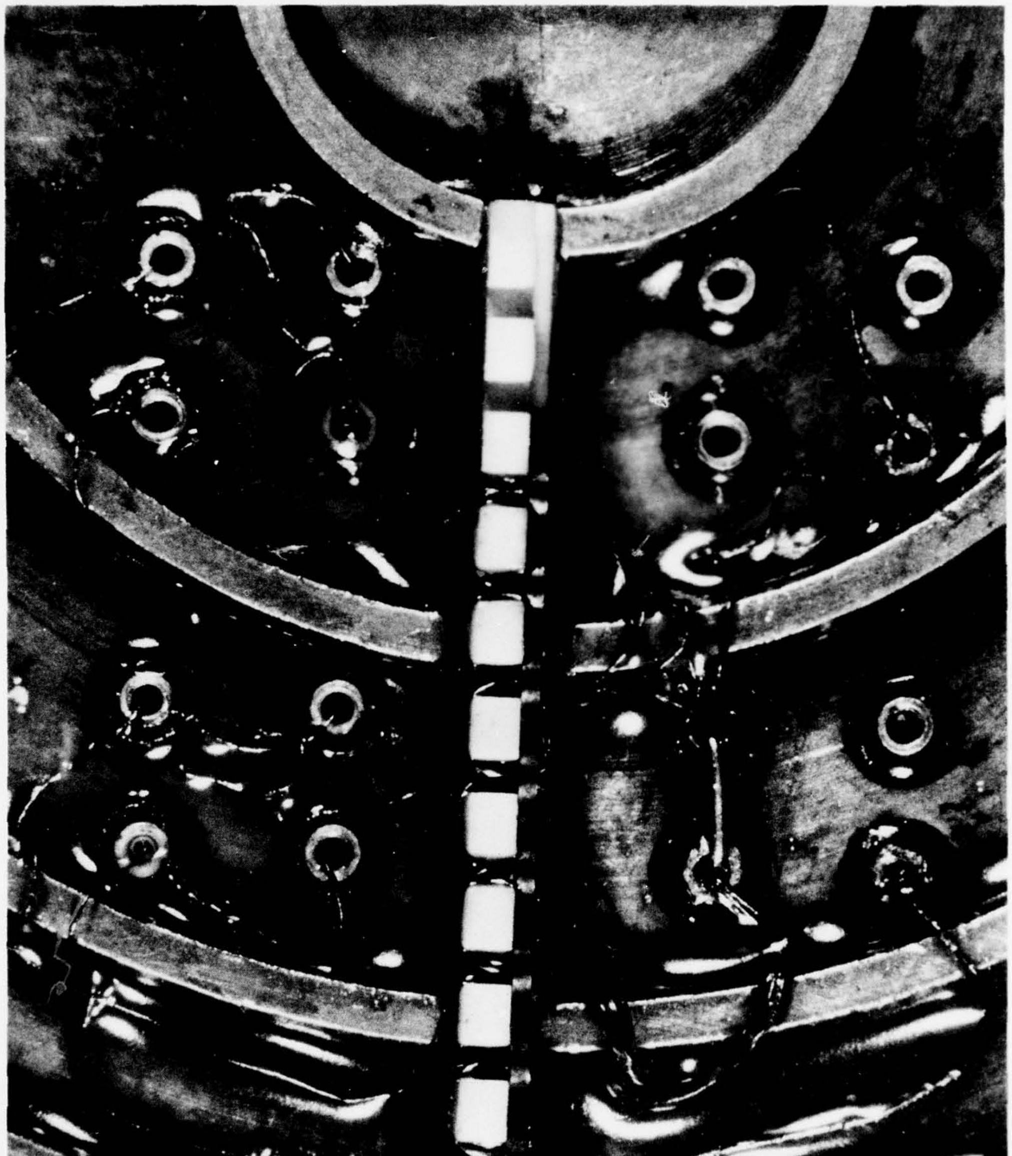


Figure 24. Improved Bit Configuration (Magnification: 9.5 x).

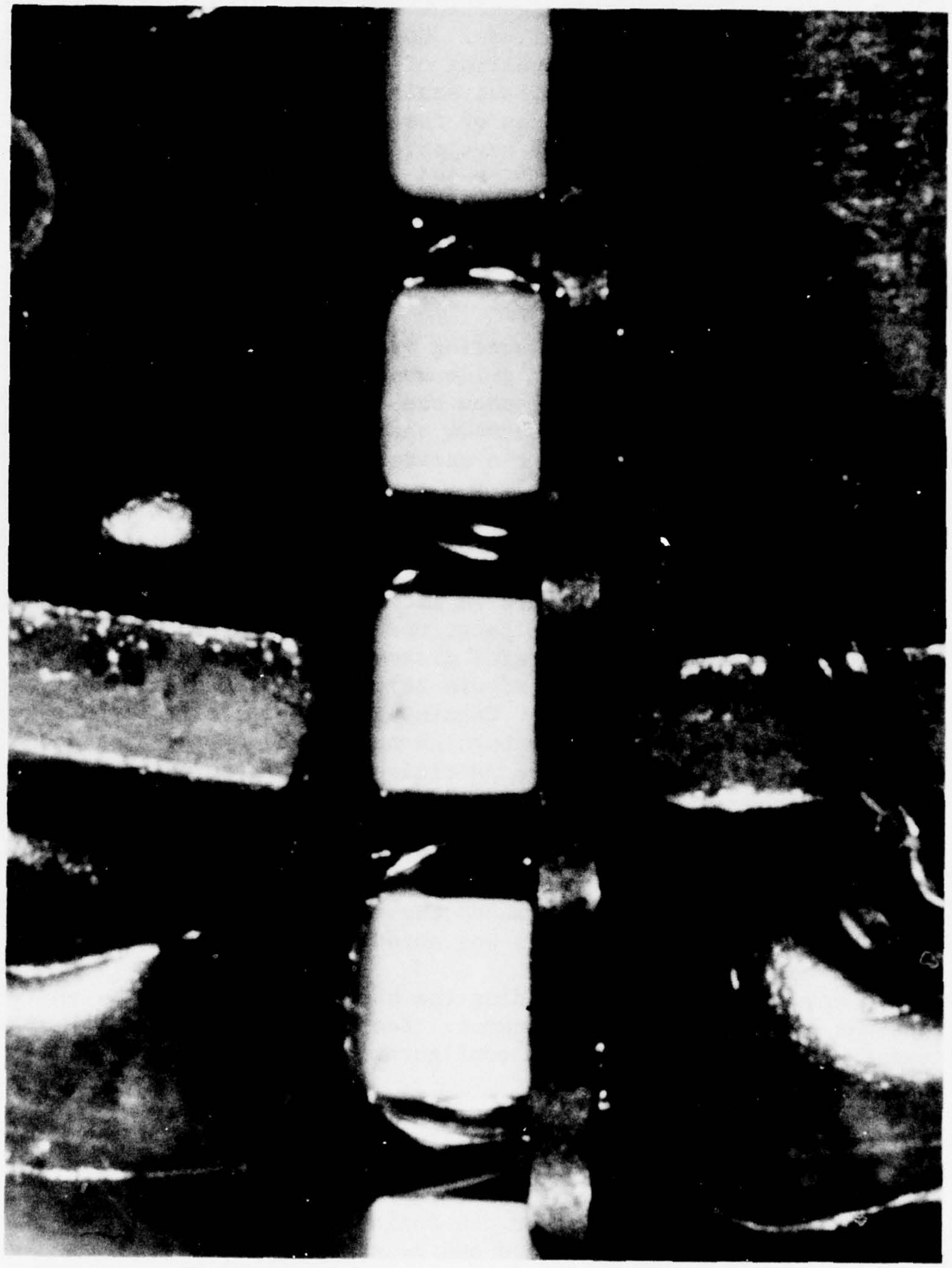


Figure 25. Bit Closeup (Magnification: 30 x).

Two operating life tests were conducted by the vendor with the encoder being driven at 3600 rpm. At 5.2×10^7 revolutions, the first test was aborted due to bearing failure. Having gone through three vibration tests was the primary cause of the bearing failure. Completing three vibration tests was considered unduly severe. Brinnelling of the races and partial disintegration of the Teflon-filled fiber glass seals accelerated the failure. After installing a new set of bearings of the same type, the life test was restarted. A total of 1.48824×10^8 revolutions was completed with no difficulty. This exceeded the required 1.2×10^8 revolutions. On disassembly, no damage or degradation of the encoder was noted.

6.3 ENGINE TESTING

For engine testing, a special mounting bracket was designed to permit the encoder to monitor the fan inlet guide vane angle on the F101 during engine operation. Figures 26 and 27 show the encoder mounted on the engine in an altitude test cell. Mounted outside the altitude tank, the electrical readout device was used to indicate the encoder output signal during engine operation. A 20-foot electrical cable was used to connect the two pieces of hardware. Earlier attempts to use cell wiring (about 100 feet) failed because of signal attenuation in the long lead length. Cable length on an engine would normally be 15 feet or less.

Early in the accumulated 25 hours an intermittent failure appeared in the LSB-2. At the completion of the test, the torque to rotate the shaft was erratic and higher than normal. Careful disassembly revealed two broken ferrite cores, LSB-1 and LSB-2 (see Figure 28). The least significant bit (LSB) showed an open output winding. Examination under a microscope revealed the three most significant bits with burnish marks made by the disk and a cut wire in the LSB output winding. Dark particles which appeared to be core material were embedded in the coil at the location of the cut wire. Apparently a large broken core segment became wedged between the coil and the disc and cut the wire. Several aluminum chips were found on the disk; chips larger than the normal 0.0015 inches clearance between the cores and the disk. One of these chips probably caused the initial core fracture of LSB-2. No abrasion of the cores by the wires was noted.

Several areas were found, including the back of the connector, where a "hot" wire was exposed to the environment. See Figure 29. Since the interior of the encoder is not sealed, such a configuration probably would not pass a humidity test.

After disassembly, the torque to rotate the shaft was relatively smooth. Wedging of core debris caused the erratic torque noted initially.

Calibration was impossible after the engine test due to the loss of three bits, two by fractured cores and one by an open output winding.

Figure 26. Shaft Encoder Mounted on F101 Engine.

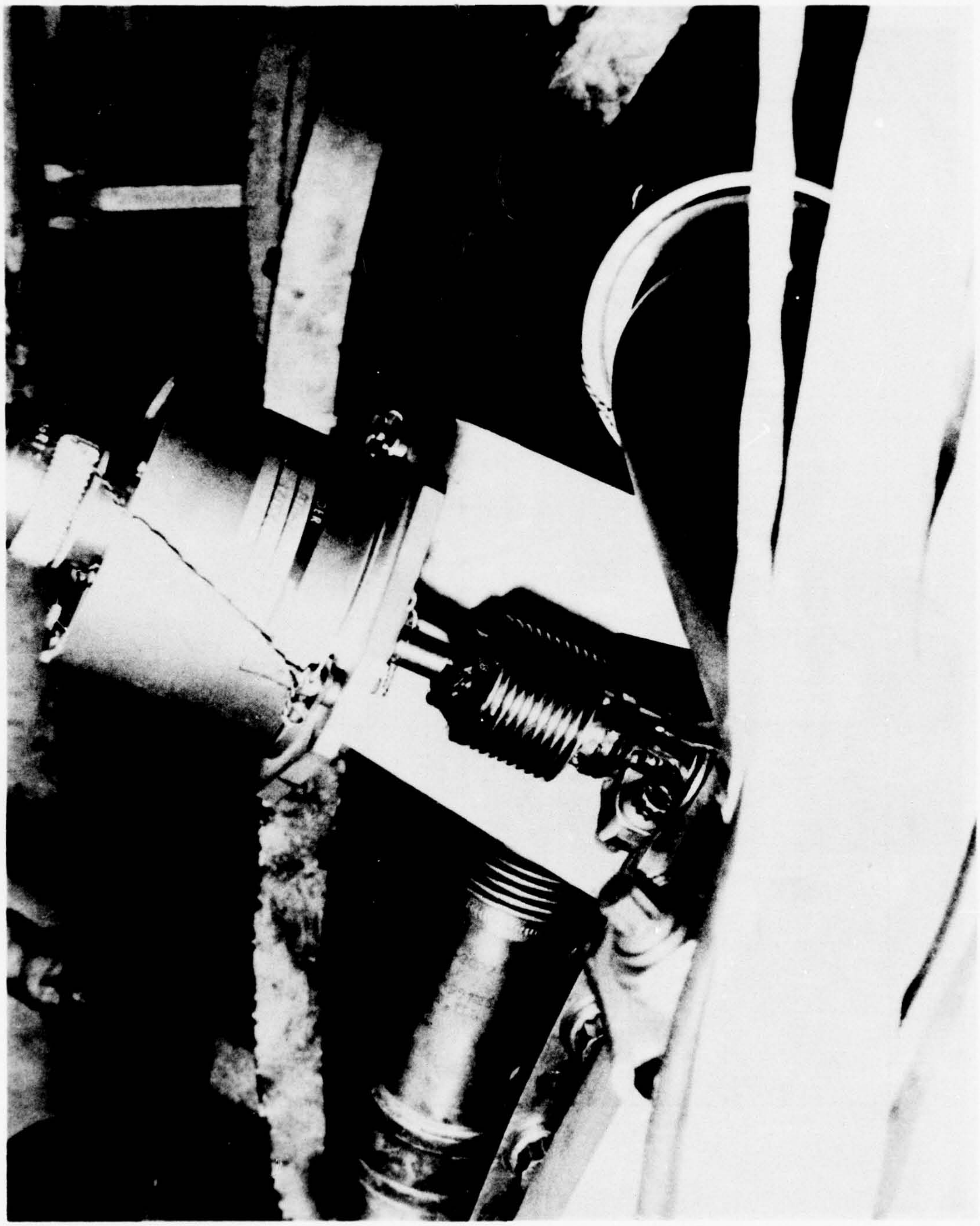


Figure 27. Shaft Encoder Mounted on F101 Engine (Closeup).

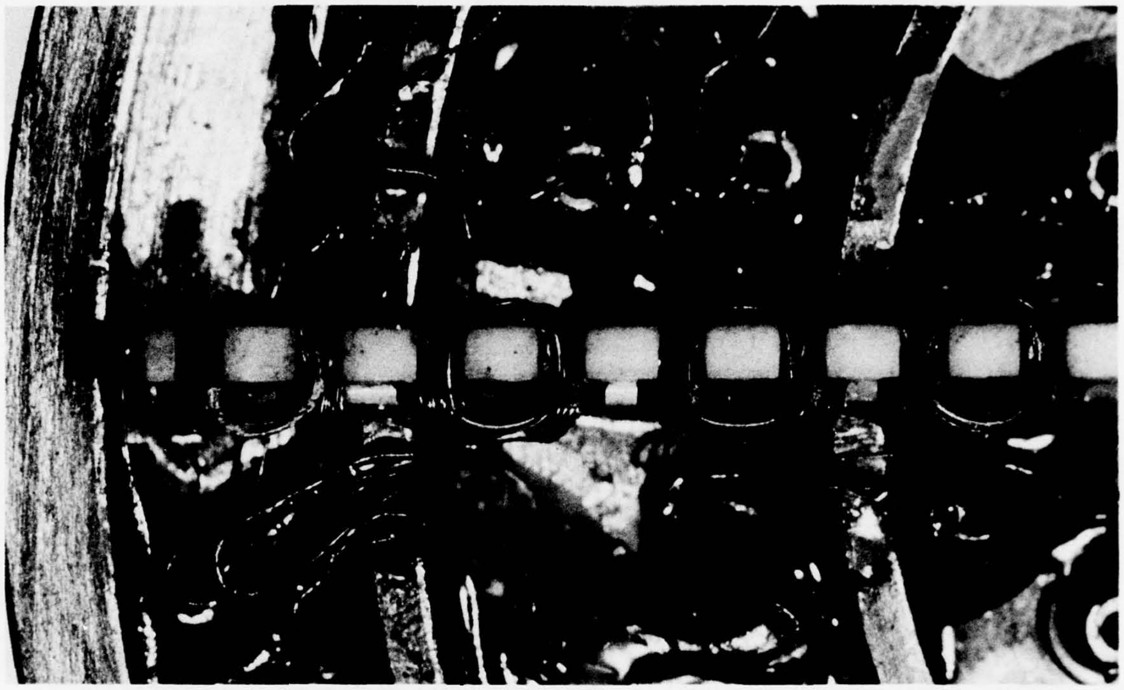


Figure 28. Fractured Cores from Engine Test.

Figure 29. Partial Disassembly of Encoder.

7.0 CONCLUSIONS

7.1 HIGH TEMPERATURE EFFECTS

A prototype magnetic digital shaft encoder built by Singer-Librascope met the life, vibration, and thermal cycling requirements as specified by General Electric Company. The inability to meet accuracy requirements at 400° F was caused by the reversible loss of permeability and saturation flux density by the ferrite cores at high temperature. This characteristic is the limiting factor in the design of high temperature magnetic shaft encoders.

7.2 DESIGN CONSIDERATIONS FOR VIBRATION AND THERMAL SHOCK

Unsupported coil wires caused a failure during the second vibration test by abrading the ferrite cores. The brittle nature of ferrite requires special design consideration in the areas of vibration and thermal shock. A configuration using reduced wire size and improved potting of the wires completed the vibration test successfully.

7.3 CONTAMINATION SENSITIVITY

Magnetic encoders are somewhat contamination sensitive as evidenced by the failures caused by built-in chips. They are particularly vulnerable to magnetic contamination which would be drawn into the critical clearance between the heads and the disk, thereby causing the cores to be fractured by input motion.

7.4 BEARING SHIELD CRITERIA

Fiber glass is not a good bearing shield material. Fragmentation of the fiber glass can cause a bearing failure. Avalanching failures should be avoided where possible. Bearing size is adequate with the preload to prevent hammering by vibration.

Reliability could be improved and weight and cost reduced by incorporating a vendor suggestion of placing all the electrical components, including the connector, on a single plate.

7.5 POWER REQUIREMENTS

Compared to analog devices, the power requirement for magnetic shaft encoders is high. Some improvement is desirable in this aspect.

7.6 EFFECTS OF CABLE LENGTH ON FREQUENCY ATTENUATION

Engine testing showed that cable length is important and should be checked for each application. The high frequency signal attenuates rapidly with cable length. Fifteen foot cable lengths on-engine should be no problem.

7.7 PACKAGING REQUIREMENTS

In the present configuration the disk and the transformer heads are both installed from the connector end of the housing, making it difficult to have a positive stop to prevent the disk from impacting on the ferrite cores.

As presently designed, the encoder would probably not pass a stringent humidity test because of the exposed "hot" wires. The wiring configuration looked very good otherwise, the leads being anchored on both the connector plate and the head holder plate.

7.8 TRADE-OFF STUDY

As the trade-off study of Table 2 indicates, the primary advantage of an encoder over an LVDT is accuracy. The principal disadvantages are failure rate and power requirements.

Table 2. Trade-Off Study of Magnetic Encoder versus LVDT.

Parameter	LVDT	Encoder	
		8 Bit	9 Bit
Excitation	7.07 volts 3 kHz 1% Distortion Sine Wave 0.2 VA	5.0 volts 50 kHz 5% Distortion Sine Wave 1.5 VA	5 volts 150 kHz Bipolar Trapezoidal Wave 1.0 VA
Size	0.6 dia X 6 in. long	2.25 dia X 1.7 in. long	2.25 dia X 1.7 in. long
Input Motion	Linear	Rotary	Rotary
Weight	0.5 pound	1.0 pound	1.0 pound
Resolution	0.000010 in.	1.4 degree	0.7 degree
Number of Leads	4	11 (5 with Parallel to Serial Converter)	12 (5 with Parallel to Serial Converter)
Failure Rate/10^6 hrs	1.9	18	18
Environmental Capability	5000 psi, 1000° F	200 psi, 260° F (400° F in Dev) Dynamic Seal	200 psi, 260° F Dynamic Seal
Signal Conditioning	• Phase Sensitive Demodulator • Analog Amplifier • A to D Converter	Gray Code to Binary Converter	Gray Code to Binary Converter
Development Status	Proven in Aircraft and Commercial Industry to 450° F	Limited Application in Aircraft Industry. Increasing use in Commercial to 260° F.	Limited Application in Aircraft Industry. Increasing use in Commercial to 260° F.
Range of Motion	± 0.005 to ± 10 inches	1/16 turn to 1 turn	1/16 turn to 1 turn
Cost	$250	$325	$350
Accuracy			
Sensor	± 0.25%	± 0.30%	± 0.15%
Electronics	± 0.25% Demodulator ± 0.20% A to D		
RSS	± 0.41%	± 0.30%	± 0.15%

8.0 RECOMMENDATIONS

Continued development of a -65° F to 400° F magnetic digital shaft encoder should be pursued, concentrating the effort on high temperature ferrite cores and more reliable construction.

A follow-on program, viewed as the next logical development step, should include nine bits with plus or minus one-half bit accuracy, a soft plastic rubbing seal (such as Teflon) to shield the bearings and protect the interior of the encoder from contamination, and simplified construction placing all electrical components on a single plate. Substantial redesign should be done to reduce the vulnerability of the ferrite cores to mechanical damage. The ceramic head holder could be reconfigured to "sweep" the disk on both sides of the cores and serve as a stop to protect the cores from any unwanted axial motion of the disk. A redesign would also need to include moisture-proofing of the wiring.

Implementation of the recommended follow-on program would be expected to achieve a prototype shaft encoder design fully capable of meeting both performance and environmental operating requirements consistent with advanced digital control postulated for the next generation of military aircraft.

APPENDIX

GE Specification HCD-1089,
Transducer, Position, Digital

TRANSDUCER, POSITION, DIGITAL

1. SCOPE

1.1 Scope. This specification, in conjunction with M50TF2, described the requirements for a rotary digital encoder to be used as a position transducer.

1.1.1 This specification contains the following classes:

Classes: A & B

1.2 Definitions. In addition to the definitions of M50TF2, the following definitions shall apply:

Electrical Rotation - The range of shaft position over which the digital count and output accuracy limits shall apply.

2. APPLICABLE DOCUMENTS

2.1 M50TF2, Class A, in its entirety, forms a part of this specification unless modified or deleted by a paragraph herein, with a corresponding paragraph number. In addition, the following publications of the issue in effect on date of request for quotations shall form a part of this specification to the extent specified herein:

MILITARY SPECIFICATION

MIL-W-22759	Wire, Electric, Fluorocarbon Insulated, Copper and Copper Alloy
MIL-I-27686	Inhibitor, Fuel System Icing
MIL-E-5009C	Engines, Aircraft, Turbojet and Turbofan, Tests for
MIL-B-5087	Bonding, Electrical & Lightning Protection for Aerospace Systems
MIL-T-5161	Turbine Fuel, Referee
MIL-G-5572	Gasoline, Aviation, Grades 80/87, 100/130, 115/145
MIL-T-5624	Turbine Fuel, Aviation, Grades JP4 and JP5

REVIEWED	REVIEWED	REVIEWED
PREPARED William L. Spencer 9-12-74	APPROVED	DISTRIBUTION

.T 9020 (2/68)

GENERAL ELECTRIC
CINCINNATI, OHIO 45215

MIL-C-7024	Calibrating Fluid, Aircraft Fuel System Components
MIL-L-7808	Lubricating Oil, Aircraft Turbine, Synthetic Base

FEDERAL SPECIFICATIONS

TT-S-735	Standard Test Fluids, Hydrocarbon
NAS 1599	Connectors, Electrical, Miniature

MILITARY STANDARDS

MIL-STD-202D	Test Methods for Electronic and Electrical Component Parts
MIL-STD-461	Electromagnetic Interference Characteristics, Requirements for Equipment
MS18001	Wire, Electric, Extruded TFE-Fluorocarbon-Insulated, Abrasion Resistant, Medium Weight Nickel-Coated Copper

ASTM SPECIFICATIONS

ASTM D1655	Aviation Turbine Fuels, Specification for

GENERAL ELECTRIC SPECIFICATIONS

M50TF3	Protective Closures
B50T75	Insulated Copper Magnet Wire

3. REQUIREMENTS

3.1 Material and Processes.

3.1.1 General. In addition to the requirements of M50TF2, Class A, material of questionable compatibility with fluids per 3.14.3.1 must be reviewed and approved by the Purchaser.

3.2 Standard Parts.

3,2.3 Electrical Connectors. Electrical connectors shall be of hermetic construction conforming to the requirements of NAS 1599 and the source control drawing except the terminals will be flattened and pierced.

3.13 Detail Design Objectives.

3.13.1 Storage Life. The transducer shall be capable of meeting the functional requirements of this specification after storage for one year as a packaged spare part or storage for two years assembled in a control.

3.13.1.1 Storage Conditions. Ambient temperature may range from -70 to 160 F remaining constant or varying at a rate as high as 108 F per minute. The unit, as a spare part, shall be stored in a sealed condition so it is not exposed to the atmosphere and is protected from shock and from strong external magnetic fields. The connector will be protected by protective closures per M50TF3, Class A.

3.13.1.2 Operating Life. The component shall have a minimum life of 13500 hours when the component has accumulated 0.5×10^6 service hours subjected to the service condition requirements of paragraph 3.14.3. Time between the overhauls shall be 2000 hours.

3.13.2 Reliability Objectives. One hundred percent operational reliability shall be a design objective.

3.14 Detail Design Requirements. The following requirements apply under all combinations of required operating conditions (including life) unless otherwise stated.

3.14.1 Physical Characteristics.

3.14.1.1 Weight. The weight of the component shall not exceed the weight specified on the source control drawing.

3.14.1.2 Balance. None required.

3.14.1.3 Electromagnetic Compatibility. The vendor shall establish a total component design approach to electromagnetic compatibility, such that when this component is integrated with the other components of the engine control system, an electromagnetically compatible system which meets the requirements of MIL-STD-461, Class F1, will result. The design shall incorporate accepted electromagnetic compatibility design practices which include but are not limited to consideration of the electrical bond of the transducer housing to the control assembly and isolation of signal leads by wire routing and twisted pairs. All wiring and electrical mechanisms shall be in electrically continuous enclosures to effectively shield them or separate them from other electromagnetic environments. AFSC Design Handbook 1-4 shall be used as a reference for design. A review of the design features to assure a good EMC design will be held sufficiently early in the development program to permit design improvements without jeopardizing the program schedule.

3.14.1.3.1 Electrical Bonding. The mounting surface of the transducer control interface shall be electrically conductive such that the DC resistance across this interface with the transducer installed in the normal manner, but without other electrically conductive connections made, shall be less than .0025 ohms when measured with a bonding meter having resolution better than .00025 ohms. Any external electrical connector shall be mounted to the transducer housing such that 360° + 0°, -20° of line contact shall be maintained between the connector shell and the housing. The mounting surfaces including finishes, of both shall be electrically conductive and the DC resistance across this interface shall be less than .0025 ohms when measured as indicated above.

3.14.1.3.2 Lead Wire Dress. The electrical lead wires shall be routed to achieve the minimum electromagnetic and electrostatic coupling between the input leads and the output leads by physical separation. In addition, the primary (input) leads and the secondary (output) leads shall be separately twisted with a minimum of two turns per inch.

3.14.1.4 Lubrication. In normal operation, the housing of the transducer may be splashed by any of the fluids specified in 3.14.3.2. No lubricant shall be required for satisfactory operation of the transducer after assembly.

3.14.1.5 Ignition Proof. The transducer shall meet the environment test (Explosion Proof) per 4.4.3.3.3 of MIL-E-5009C.

3.14.1.6 Fungus Proof. The transducer shall be capable of meeting the requirements of the fungus test per 4.4.3.3.2 of MIL-E-5009C.

3.14.1.7 Leakage. The ambient end of the transducer shall be protected against the entry of airborne contaminants, including corrosive vapors, or all internal coils, wiring, terminals and associated junctions shall be protected against contact with those elements of contamination to the extent that no deterioration of the capabilities of the transducer to meet the requirements of this specification shall exist.

3.14.2 Life Requirements.

3.14.2.1 Service Life. The service life of the transducer shall exceed 2000 hours without overhaul.

3.14.2.2 Maintenance. Through the entire range of service conditions and the normal service life of the device, neither adjustments nor other servicing shall be required to accomplish satisfactory performance.

3.14.3 Service Conditions. The transducer shall meet all requirements when subjected to any conditions imposed as specified in 3.14.3.1. The extreme range conditions will not be encountered during more than 2 percent of the operating life of the transducer.

3.14.3.1 Environmental Conditions and Imposed Stresses.

PARAMETER	NORMAL RANGE	EXTREME RANGE
Pressures (psia) Ambient (air)	.5 - 35	
Temperatures (F) Ambient (air)	Class A Class B -65 - 400 -65 - 250	Class A Class B -65 - 400 -65 - 250
Electrical Input Supply	5.0 RMS volts, 50000 ± 1000 Hz Sine Wave 1.5 va	
Other Conditions Air Velocity Maneuver Forces	20 ft/sec maximum 10 g's, any plane, maximum	
Vibration - See Figure 1		

3.14.3.2 Fluids.

(a) Primary Fuels. The transducer shall fulfill all detail requirements with either of the following primary fuels: MIL-T-5624, Grade JP4 or JP5.

(b) Alternate Fuels. Fuels in accordance with ASTM D1655, A & B and NATO equivalents shall be accommodated as alternate fuels.

(c) Emergency Fuels. Fuels in accordance with MIL-G-5572, Grade 115/145, shall be accommodated as emergency fuel.

(d) Calibration Fluid. Fluid in accordance with MIL-C-7024, Type II, filtered to 10 micron impurity shall be used for calibration and acceptance testing of the controls of which this transducer will be a part.

(e) Qualification Fluid. Fuel in accordance with MIL-T-5161, Grade I or Grade II, or TT-S-735, Type I, shall be accommodated as qualification test fluid for the engine life with which the transducer as a part of the engine control is to be used.

3.14.3.3 Fluid Contamination. The transducer shall meet its operating requirements when operating with the housing splashed with fuel contaminated per Table I and subsequently filtered through a 74 micron absolute filter.

3.14.4 Construction.

3.14.4.1 Coils. The transducer coils shall be constructed from double insulated magnet wire in accordance with B50T75, Class B. Wire size not to be less than No. 37 AWG (.0045 inch diameter). Coils shall be isolated from any contact with the operating fluids surrounding the transducer. Coils shall be fixed or retained so that the shift resulting from changes in the transducer temperature may be readily predetermined from the relative temperature coefficients of expansion of the materials used in the transducer construction.

3.14.4.2 Lead Wires. Lead wires shall be firmly attached to the transducer coils and shall be of high temperature wire, insulated with polytetrafluoroethylene. Lead wires shall be no smaller than No. 26 AWG. (Suggested lead wires conform to the requirements of MIL-W-22759 per MS18001.)

3.14.4.2.1 Lead wire lengths shall permit ready access to connector terminations for soldering and shall have sufficient length to permit repair replacement of any damaged connector.

3.14.4.3 Wire Connections. Lead wires and terminals shall be interconnected by high temperature solder (or by other methods approved by the purchaser) to provide good mechanical and electrical joints. The same shall apply to the junctions produced at the transducer coils.

3.14.4.4 Magnetic Shielding. The transducer shall be magnetically shielded to minimize the stray coupling with any surrounding magnetic fields.

3.14.5 Reliability Indices. The component shall meet or exceed the following reliability component goals at a point in time equal to 500,000 cumulative service hours.

(a) Mission Power Loss Failure Rate (component caused) equal to 2.0 events per 10^6 service hours. MTBF = 200,000

(b) Unscheduled Engine Removal Failure Rate (component caused) equal to 0.5 events per 10^6 service hours.

3.14.6 Functional Design Requirements.

3.14.6.1 Operating Conditions. The transducer shall meet all requirements when excited and terminated as specified.

3.14.6.1.1 Excitation. The excitation will be 5.00 RMS volt sine wave at 50 ± 1 Khz with less than 5.0 percent distortion.

3.14.6.1.2 Termination. The transducer will be terminated in a pure resistive load of 10,000 ohms.

3.14.6.2 Input Requirements. The required input to the transducer shall not exceed 1.5 volt-ampere.

3.14.6.3 Output Impedence. The output impedence of the transducer shall not exceed 500 ohms.

θ 3.14.6.4 Readout Parameters.

3.14.6.4.1 Range. The range of the input shaft shall be one revolution.

3.14.6.4.2 Direction. Increasing count for CW rotation of shaft (viewed from shaft end).

3.14.6.4.3 Type. Magnetic gray code, linear.

3.14.6.4.4 Resolution. 256 counts per turn.

3.14.6.4.5 Accuracy. Within the requirement that the output must never be ambiguous, the total error will not exceed one bit.

3.14.6.5 Rotation. In normal operation the rotation will be less than one turn at a maximum speed of 250 rpm. Mechanically, the transducer should be capable of continuous rotation with the torque not to exceed 2 in. ounces.

θ 3.14.6.6 Output. Maximum "zero" output will be 0.40 volts half amplitude. Minimum "one" output will be 2.8 volts half amplitude.

3.14.6.7 Ball Bearings. The shaft ball bearings will have separators and be sealed from the transducer ambient. Lubricant will be General Electric G-300 silicone grease.

3.14.6.8 Insulation Resistance. The insulation resistance of all the circuits connected to the terminals of the connector shall be such that with an applied voltage of 100 volts DC across those terminals to ground the resistance shall exceed 100 Megohms.

3.14.6.10 Dielectric Strength. The dielectric strength of the transducer insulation shall be such that the voltage of 3.14.6.8 can be applied as indicated for a period of not less than one minute with no decrease in the measured resistance.

3.14.7 Thermal Cycling. The transducer shall be subjected to a minimum of three thermal cycles in accordance with MIL-STD-202D, Method 107B, Test Condition C, with normal excitation and termination and with the output monitored. The transducer shall be subjected to the maximum temperature specified per 3.14.3.1 without failure and shall meet the inspection test requirements of 4.3.3 after thermal cycling.

4. QUALITY ASSURANCE TESTS

4.3 Types of Component Tests.

4.3.1 Design Assurance Tests.

4.3.1.1 Vibration Testing. Vibration tests shall be performed in accordance with MIL-STD-202C, Method 204A, Test Condition C, except as further specified herein and shall be performed with the input energized and output terminated as specified in 3.14.6.1. The output shall be monitored during the varying frequency scans. Output monitoring during endurance operation at points of resonance is optional. The transducer shall be mounted in a fixture simulating actual operating conditions.

4.3.1.1.1 Vibration Scans. Vibration scans shall be run over the range of frequencies from 10 Hz to 2000 Hz at an amplitude limit of .060 inch peak to peak or at an acceleration of 20 g, whichever is less severe. Prior to any endurance vibration, scans shall be run with the armature at positions equivalent to full electrical count and at a point in the electrical rotation range equal to 90 degrees from "one". Following all endurance vibration operation, scans shall again be run with the same shaft positions. Any point of greatest disturbance of the electrical output during the initial scans shall be points at which endurance runs shall be conducted. If there is a difference in vibration response in the output with shaft position, the shaft shall be positioned to the point of maximum output disturbance for the vibration endurance run. If electrical or mechanical resonances differ from the pre-endurance to post-endurance scans, these differences will be noted.

4.3.1.1.2 Vibration Endurance. Total vibration endurance will amount to 10^7 cycles and will be apportioned between the points of maximum response as determined during the pre-endurance scans as agreed upon by the vendor and the purchaser.

4.3.1.2 Mechanical Stroke. Measure the free and unencumbered rotation of the shaft. The shaft shall be capable of continuous rotation.

4.3.1.3 Input Requirements. At room temperature, excite and terminate the transducer with maximum voltage and minimum load resistance per the limits of 3.14.6.1 and measure the current. The product of the applied voltage and the current shall not exceed 1.5 volt-ampere.

4.3.1.4 Output Impedance. Excite the transducer per 3.14.6.1.1 measure the output impedance at the calibration temperature of 77F (25C). The output impedance shall be less than 500 ohms.

4.3.1.5 Dielectric Strength. Measure the dielectric strength by a determination of the effective resistance between all circuits tied together and ground.

After the application of the 100 volt potential difference for a minimum of one minute, measure the resistance without removing potential. The measured value of the resistance shall not be less than 100 megohms.

4.3.2 Certification Tests.

4.3.2.1 Component Certification Test. A component built to production drawings shall be tested for performance, endurance and environmental capabilities in accordance with MIL-E-5009C or to equivalent tests specified by the purchaser.

4.3.2.2 Vibration. Perform the vibration test as specified in paragraph 4.3.1.1

4.3.2.3 Life. Rotate the transducer shaft for 1.2 $(10)^8$ revolutions at 1800 rpm at room temperature. Reverse direction of rotation once per hour. The transducer shall be continuously excited and terminated during the life test and the output observed at intervals not to exceed 5 hours to assure its operability.

4.3.2.4 Impact Tests. The transducer shall be subjected to 10 impacts of 30 g's with a time duration for each impact of not less than 10 milliseconds in each of its three mutually perpendicular planes. Sufficient data shall be taken both before and after this testing to identify the effects of the impact upon transducer performance.

4.3.2.5 Checkout. Prior to and immediately after conducting any of the component certification tests of 4.3.2, the transducer shall be operated at the calibration temperature and data taken to determine the extent of its continued compliance with the inspection test requirements of 4.3.3.

4.3.3 Inspection Tests. These tests are specified to provide assurance that each transducer is within the required limits to insure its proper function when installed as a feedback device in a control.

4.3.3.1 Examination of Product. Each unit shall be examined to assure conformance to the requirements of the drawing and such tests as are prescribed in 4.3.3 performed to assure proper function.

4.3.3.2 General Test Conditions.

4.3.3.2.1 Standard Conditions. Whenever ambient conditions (temperature and pressure) are not specified for a test, the test shall be performed at an ambient pressure equivalent to sea level ± 1000 feet and an ambient temperature of 77 ± 20F. The temperature shall be logged and corrections made where necessary. In the event of corrections, the "raw" data and correction factors shall be provided along with the corrected data.

4.3.3.2.2 Measurements. The accuracy of the instruments used to make measurements shall be verified.

4.3.3.2.3 Test Data. Test data shall include a list of the test instruments used in conducting the tests, the date of the last calibration and where corrections to the readings have been required because of calibration errors, the tabulated corrections or a calibration or deviation chart. The data sheets shall carry a reference to the particular paragraph of this specification to which the test being recorded applies and all data shall be recorded. If any test or part of a test is re-run, all data shall be included and the reason for the re-run clearly stated thereupon. A minimum of three copies of the data shall be included with the transducer when shipped.

4.3.3.3 Output. Measure output versus shaft rotation. The transducer shall meet the requirements of paragraphs 3.14.6.4.5 and 3.14.6.6.

4.3.3.4 Insulation Resistance. Measure insulation resistance. The requirements of paragraph 3.14.6.8 shall be met.

4.4 Test Accuracy. In lieu of the requirements of M50TF2, Class A, the setting error, reading error and instrument error when combined on a root mean square basis shall not exceed 10 percent of the tolerance of the test parameter requirements in question.

5. PREPARATION FOR DELIVERY

The transducer shall be packaged in a manner to protect it from the hazards normally encountered in shipping and storage.

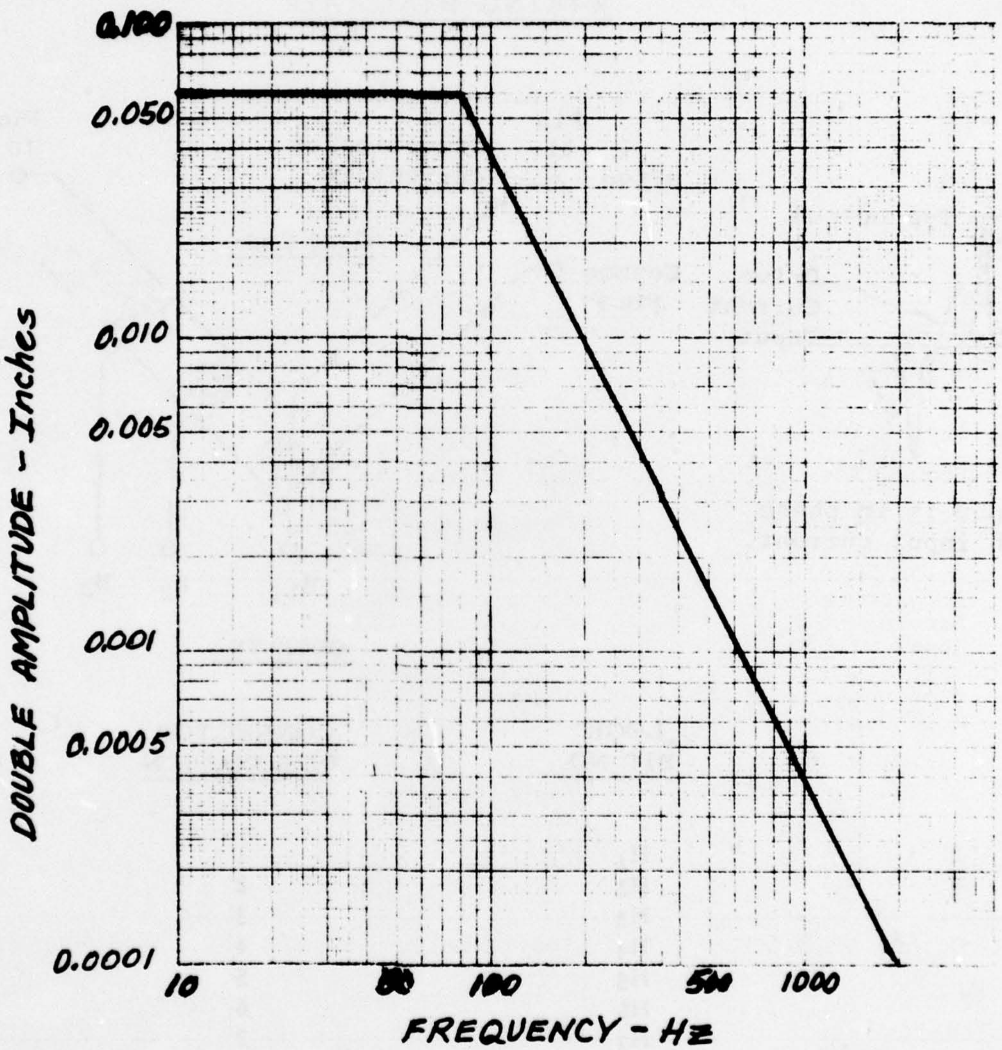
6. NOTES

6.1 Classification of Characteristics.

Critical:	none
Major:	3.14.6.4 3.14.6.6
Minor	All other paragraphs

Table I - Fuel Contaminants

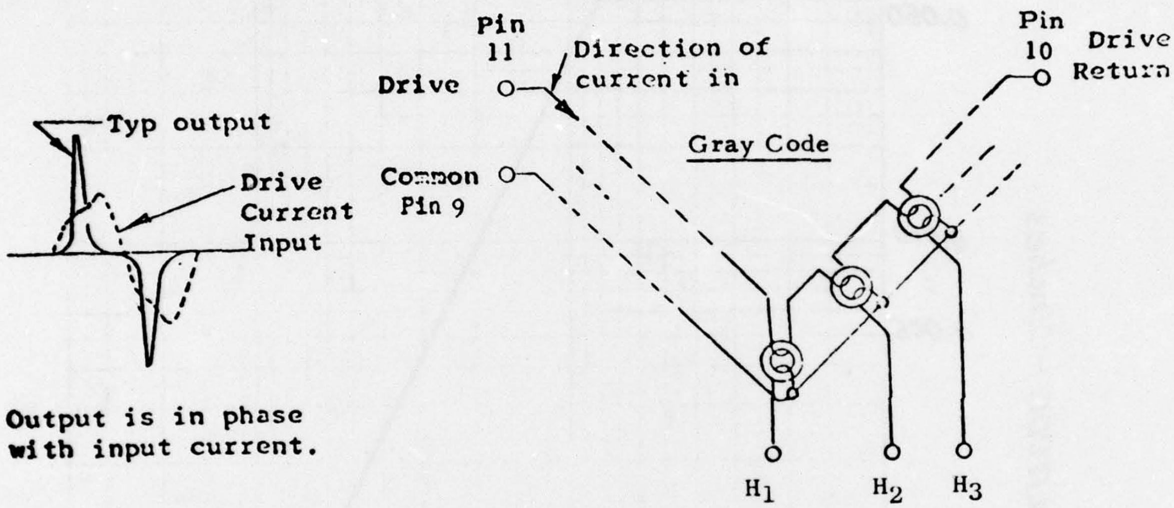
CONTAMINANT	PARTICLE SIZE	QUANTITY
Iron Oxide	0-5 Micron	28.5 gms/1000 gal
Iron Oxide	5-10 Micron	1.5 gms/1000 gal
Sharp Silica Sand	300-420 Microns	1.0 gms/1000 gal
Sharp Silica Sand	150-300 Microns	1.0 gms/1000 gal
Prepared dirt conforming to A.C. Spark Plug Co. Part No. 1548687 (Coarse Arizona Road Dust)	Mixture as follows: 0-5 microns (12 percent) 5-10 microns (12 percent) 10-20 micron (14 percent) 20-40 micron (23 percent) 40-80 micron (30 percent) 80-200 micron (9 percent)	8.0 gms/1000 gal
Cotton linters	Staple below 7 (U.S. Department of Agriculture Grading Standards)	0.1 gms/1000 gal
Crude naphthenic acid		0.03 percent by volume
Salt water prepared by dissolving salt in distilled water or other water containing not more than 200 parts per million of total solids	4 parts by weight of NaCl 96 parts by weight of H_2O	0.01 percent by volume entrained



VIBRATION SCHEDULE

FIGURE 1

WIRING DIAGRAM



OUTPUTS

LOGIC BIT NO.	CONNECTOR DESIGNATION
H_1	1
H_2	2
H_3	3
H_4	4
H_5	5
H_6	6
H_7	7
H_8	8
Drive In	11
Drive Return	10
Output Common	9

FIGURE 2

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